26. J. Verstaten, J.E. Romain, and V. Veverka. The Belgian Road Research Centre's Overall Approach to Asphalt Pavement Structural Design. Proc., 4th International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Vol. 1, Aug. 1977, pp. 298-324.
27. C.L. Monismith, K.E. Secor, and E.W. Blackmer. Asphalt Mixture Behaviour in Repeated Flexure. Proc., Association of Asphalt Paving Technologists, Vol. 30, 1961, pp. 188-222.
28. P.S. Pell and K.E. Cooper. The Effect of Testing and Mix Variables on the Fatigue Performance of Bituminous Materials. Proc., Association of Asphalt Paving Technologists, Vol. 44, 1975, pp. 1-37.
29. M.W. Witczak. Pavement Performance Models Repeated Load Fracture of Pavement Systems. Report 5-76-15, FAA DOT-FA 73WAI-377. FHWA, U.S. Department of Transportation, Vol. 1, 1977, 193 pp.

Publication of this paper sponsored by Committee on Flexible Pavements.

# Load Rating of Light Pavement Structures

**KOON MENG CHUA and ROBERT L. LYTTON**

ABSTRACT

A new approach to determining the damage that overweight vehicles can do to light pavement structures is described. This procedure uses deflections measured with either the Dynaflect or the falling weight deflectometer to determine the number of passes of a specific load that will cause a critical level of rut depth in a light pavement structure. This method was based on field observations and ILLI-PAVE, a finite element pavement analysis program. In the study, a hyperbolic curve is used to describe both the stress-softening and the stress-hardening form of load deflection characteristics observed on light pavements. A method of determining the nonlinear elastic material properties for the base course and the subgrade using the falling weight deflectometer or the Dynaflect was developed. From the data collected with the pavement dynamic cone penetrometer, it appears that the stiffness of the granular base course depends, not surprisingly, on the degree of compaction of the material. The model adopted for accumulated permanent deformation due to repetitive loading and reloading follows a hyperbolic-shaped load deflection curve with a linear unloading path. Thick pavements, which are usually the stress-hardening type, appear to be more resistant to rutting. The new approach is shown to be accurate in predicting the development of rut depth with repeated loads applied by a variety of different vehicles. A computer program is written to incorporate the complete analysis method.

As a result of increasing industrial and agricultural activities, heavier trucks and higher traffic volumes have accentuated the problem of load rating and zoning of various farm-to-market roads that have light pavement structures. In evaluating overweight vehicle permit applications, the present practice in Texas is to determine the gross allowable loads on the light pavement structure by performing Texas triaxial tests on cored samples (C. McDowell, Wheel Load Stress Computations Related to Texas Highway Department Triaxial Method of Flexible Pavement Design, unpublished report of the Texas Highway Department). A more efficient, nondestructive testing method of determining damage to pavements by overweight vehicles is needed.

The new approach is a computerized procedure that uses results obtained from the Dynaflect or the falling weight deflectometer (FWD) to determine the number of passes of a specified load that will cause a critical level of rut depth in a light pavement structure. Conversely, the maximum allowable load on a light pavement structure can be determined using rut depth as a criterion for unacceptability. Rut depths are caused by accumulating pavement deformation under repeated load applications. Each time a load passes, the pavement fails to rebound as much as it was deflected under load. Establishing the difference between the loading and the unloading path is critical to making a reliable prediction of rut depth. Some of the advantages of the new approach are

1. Nondestructive testing (NDT) will reduce the time and the manpower currently required to deter-

mine the maximum load allowed on a pavement, will expedite permit evaluation, and will reduce the costs of the overall process;

2. Estimating the maximum allowable number of applications of load on a pavement will assist in planning and budgeting decisions that are related to patterns of future development; and

3. The method will assist in evaluating the economic impact of load-intensive industries on the local road maintenance and rehabilitation budget.

## DATA COLLECTION

This involved the nondestructive testing of 78 pavement sections from 12 farm-to-market roads using the Dynaflect and the falling weight deflectometer. In addition, construction drawings were used to determine the layer thickness of those sections tested and these were checked using a pavement dynamic cone penetrometer. These data formed the basis for the development of the determination of the load deflection model using the two nondestructive methods.

### Location of Test Sites

The pavement sections tested are located in Brazos and Burleson Counties of District 17 in a climate where annual rainfall and evapotranspiration are nearly balanced and hard freezes rarely occur. The pavement sections are representative of some of the weaker subgrade conditions that occur in the state.

### Test Sections

The test sections were chosen to be at mileposts (spaced 2 mi apart) along the farm-to-market roads. These sections represent a diverse sampling. Some were constructed or reconstructed as early as 1953 and as late as 1981. Table 1 gives the farm-to-market (FM) roads that were tested, the base course thicknesses, and the field-observed base course material type. Figure 1 shows typical cross sections of these roads. Base course thicknesses range from 4 to 14 in. Base course materials were found to consist of crushed stone, river gravel, sandstone, and iron ore. The surface courses or wearing courses, although originally intended to be only a surface treatment course, were measured to be about an inch thick. This is due to numerous seal coat applications.

The falling weight deflectometer and the Dynaflect were used on each section. Usually two or three sections spaced about 10 ft apart were tested at each of the selected mileposts. Measurements were made at points between the wheelpaths where the traffic is slight in order to obtain a more consistent evaluation of the overall integrity of the pavement.

**TABLE 1 Relevant Construction Details of Test Sections in District 17**

| Road Name | Mile Post No. | Base Course Thickness (in.) | Field Identified Base Course Material Type |
|---|---|---|---|
| Burleson County | | | |
| FM 3058 | 2 to 10 | 6 | Crushed stone (caliche) |
| FM 908 | 10 | 8 | |
| FM 1361 | 6 to 10 | 8 | |
| FM 2000 | 8 to 10 | 7 | Crushed stone and sandstone |
| | 12 | 6 | Gravel |
| FM 2155 | 2 to 4 | 6 | River gravel |
| FM 50 | 2 to 4 | 7.5 | River gravel |
| | 6 to 16 | 7.5 | Crushed stone |
| Brazos County | | | |
| Old Spanish Road | 2 to 4 | 14 | Crushed stone (caliche) |
| FM 974 | 6 to 8 | 4 | Crushed stone (iron ore) |
| FM 1179 | 4 | 6 | Crushed stone and gravel |
| FM 1687 | 2 | 9 | Gravel |
| FM 2038 | 8 to 10 | 10 | River gravel |
| FM 2776 | 0 to 2 | 6 | River gravel |

### Falling Weight Deflectometer

The Dynatest 8000 FWD test system (1,2) was used in this study. The FWD itself is a lightweight, trailer-mounted unit. It can deliver an impulse load of from 1,500 to 24,000 lb to a pavement. The impulse is essentially a half sine curve with a duration of 25 to 30 milliseconds. The load is transmitted to the pavement through a 12-in.-diameter loading plate that rests on a thick rubber pad that is in contact with the pavement surface. In principle, the force applied to the pavement is dependent on the mass of the drop weights used, the height of the drop, and the spring constant of the rubber pad as well as that of the overall pavement. In practice, however, the applied force is changed by varying the mass of the drop weights or the height of the drop, or both. The actual load relayed to the pavement is measured by the load cell located just above the loading plate. The deflection basin is obtained by monitoring the deflections at seven locations on the pavement surface using velocity transducers. One of these is located in an opening in the center of the loading plate.

In the tests the height of drop and the weight were adjusted to produce four different load levels: 9,000, 11,000, 15,000, and 23,000 lb, the exact magnitude of which was registered by the load cell. Figure 2 shows the locations of the deflection sensors and a set of typical deflection basins observed at the four different load levels.

### Dynaflect

The Dynaflect (3) is the most commonly used NDT device in the United States for the purpose of pavement evaluation and design. This equipment is a dynamic force generator mounted on a covered trailer. The cyclic force is produced by a pair of counter-rotating unbalanced flywheels, and this force oscillates in a sine-wave fashion with an amplitude of 500 lb at a frequency of 8 cycles per second. This force, together with the dead weight of the trailer, which is about 1,600 lb, is transmitted to the ground via two steel wheels placed 20 in. apart. The peak-to-peak deflections are measured by five geophones placed at 1-ft intervals with the first directly between the wheels. A typical deflection basin is shown in Figure 3.

## DATA ANALYSIS

After it was verified that ILLI-PAVE with appropriately assumed material models can reproduce measured deflection basins, the computer program was used to generate deflection basins for four different load levels with different combinations of assumed material models for the base course and the subgrade; different thicknesses of base course were used. These finite element computations were made to simu-

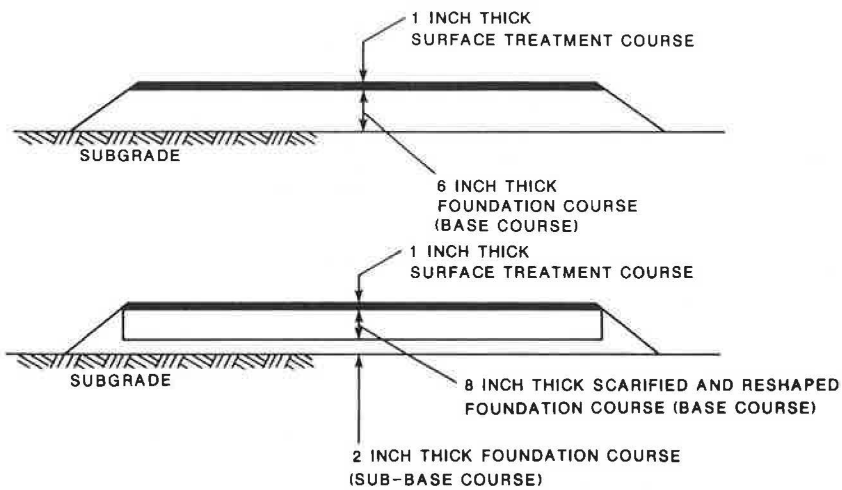



FIGURE 1 Typical cross sections of farm-to-market roads.

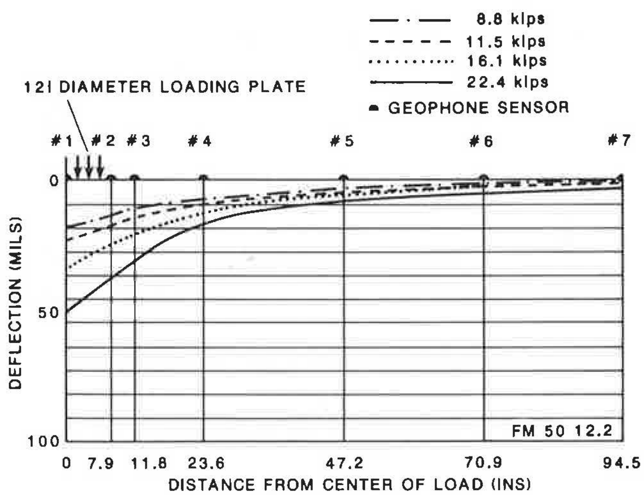



FIGURE 2 Typical deflection basin—falling weight deflectometer.

late tests done with an FWD. It was assumed that the last deflection sensor reading, which is 94.5 in. from the center of the loading plate, is related to subgrade material type.

After a procedure for identifying material models from FWD deflection sensor readings had been developed, a load deformation equation was formulated for each set of deflection sensor readings. A hyperbolic load deflection model was adopted and a means of determining the unknown coefficients was established.

The load rating or rutting model used is one that allows for a linear unloading path in the load deflection curve. The reloading path was assumed to be the same as the loading path. The gradient of the unloading path was determined from actual rut depth and the number of passes of a known load, or estimated from a formulation presented in this study, which was based on backcalculation from observed rut depths. Finally, on the basis of comparisons of deflection basins from the FWD and the Dynaflect, a correlation between the first and the last deflection sensor readings of both instruments was made.

The analytical approach adopted, the analytical tools used, and the assumptions made are discussed in the next section.

## ILLI-PAVE: Finite Element Analysis

ILLI-PAVE (4,5) is a finite element program that models an asymmetrical solid of revolution as shown in Figure 4 and allows for linear as well as nonlinear stress-dependent elastic moduli for granular and fine-grained soils. This program has been shown

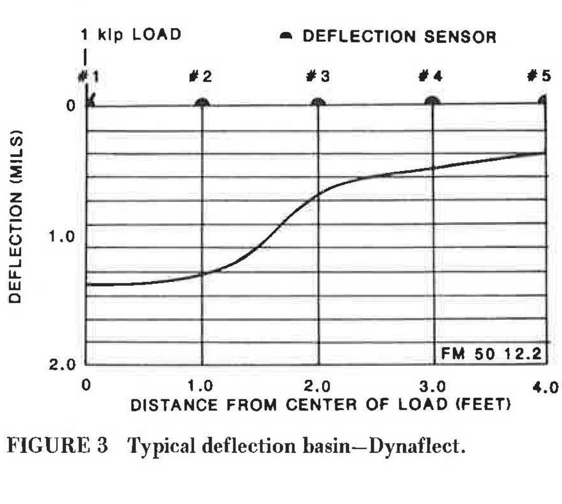



FIGURE 3 Typical deflection basin—Dynaflect.

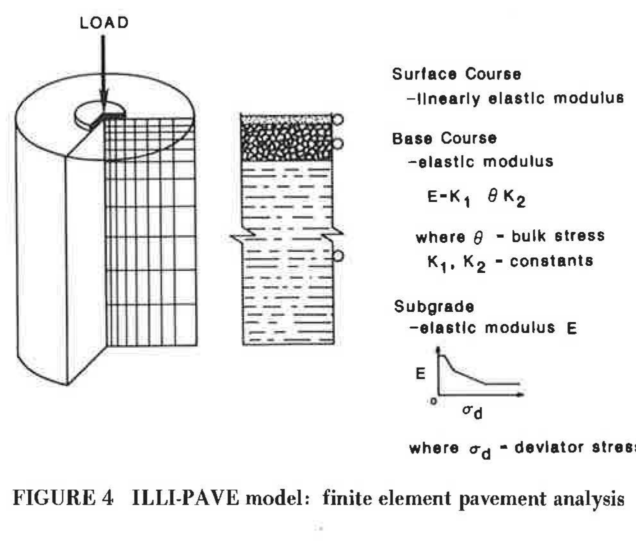



FIGURE 4 ILLI-PAVE model: finite element pavement analysis

to be adequate in predicting the response of flexible pavement to load (6).

For the analyses done in this study, a mesh of 121 elements was used. The elements were smallest nearest the pavement surface to allow for greater accuracy in computation. To allow for an adequate simulation of the boundary conditions, it was suggested (7) that the depth of the mesh be at least 50 times the radius of the circular loading plate of the FWD, which is 6 in., and that the horizontal extent be at least 12 times that radius away from the center of the loading plate. In this case, to accommodate the last FWD deflection sensor, a width of 96 in. was used. However, from the analyses made at about 11,000 lb loading, vertical stresses caused by the load input appear to be negligible beyond a depth of about 12 times the radius of the loading plate.

How ILLI-PAVE was used in this study and the material models that were input are described in the following subsections.

### Pavement Material Models

The farm-to-market roads encountered generally have three distinct layers: a surface course, a base course, and a subgrade. Some older roads were found to have a subbase consisting of the old road base that was partly scarified and then overlaid with new base course material. The subgrade material was found to vary consistently along the road.

A pavement dynamic cone penetrometer (DCP) (8) was introduced to check the thickness of pavement layers by detecting when the stiffness changed. This device consists of a steel rod with a 60-degree cone of tempered steel at one end. A sliding hammer of about 17.6 lb falling from a height of 22.6 in. provided the consistent impact load required to penetrate the pavement. The penetration given as inches per blow gives an indication of the stiffness of the pavement layers. This instrument was found to be useful for comparing the stiffnesses of the base courses encountered in this study. Figure 5 shows the DCP.

The 1-in.-thick surface courses did not contribute much to the pavement in terms of rigidity but were nevertheless included in the material modeling in recognition of their presence. An assumed modulus was used for this material in all of the analyses because the actual value of the modulus has virtually no influence on the results. The base course thicknesses used in the simulation were taken from construction drawings. However, the thicknesses found using the DCP differed from the design value by as much as 5 in. for an 8-in.-thick base course. However, in most cases the difference was much less. In the ILLI-PAVE analyses, the subbase course, if any, was considered as part of the base course because its material type did not appear to be different. As a point of interest, from the DCP data it appeared that most old pavements show a distinct interfacial layer between the base course and the subgrade. This might be due to infiltration of fines from the subgrade into the base course layer as well as to the presence of moisture.

Base course materials were found to be of the granular, unbound type. Using the DCP it was found that knowledge of the material hardness and shape is not sufficient to categorize its load deflection behavior. Figure 6 shows the rate of penetration of the DCP into a few pavements with different base course materials. It appeared that the major determining factor of the stiffness of the material is the unit weight, that is, the degree of compaction of the material. This had been realized earlier (9).

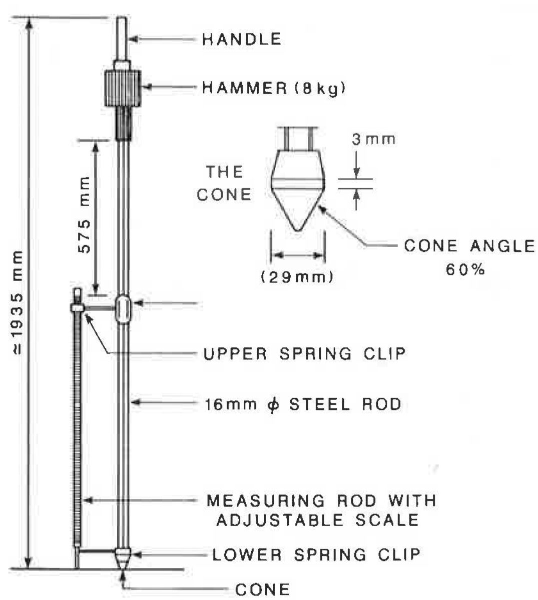



FIGURE 5 Dynamic cone penetrometer (8).

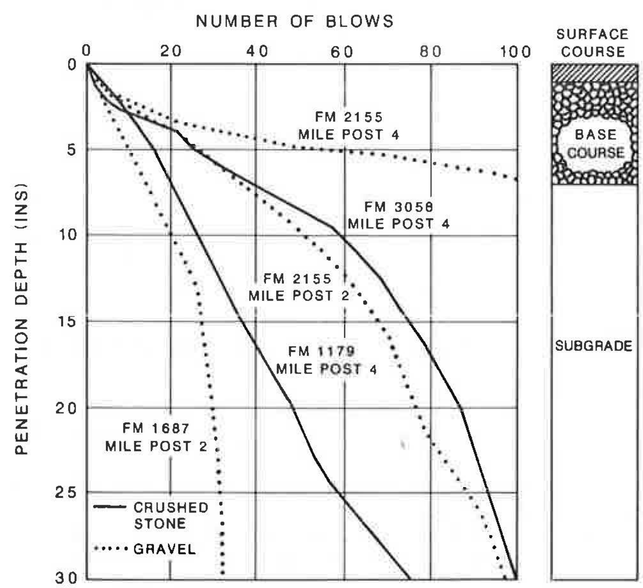



FIGURE 6 Comparison of pavement stiffnesses using the dynamic cone penetrometer.

The elastic modulus of the base course material was expressed as

$$E = K_1 \theta^{K_2} \qquad (1)$$

where

$\theta$ = the bulk stress or the first stress invariant and
$K_1$ = the unknown coefficient defining the material.

This value shall be referred to as the $K_1$-value hereafter. The range of $K_2$-values was reported to be between 0.30 and 0.60 (10;11,pp.256-266). Most

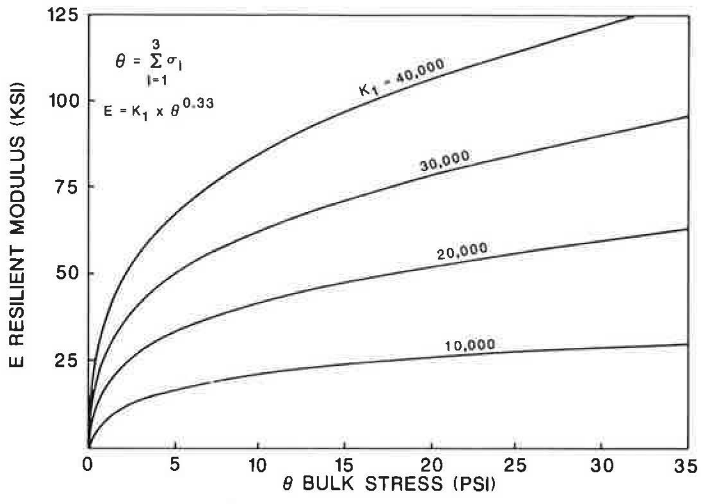



FIGURE 7 Base course material models.

analyses using ILLI-PAVE (4,10) adopt a range of from 0.30 to 0.33 for this value. For practical reasons, in this study a value of 0.33 was assumed. This reduces to one the number of factors to be identified in the base course material. Subsequent analyses showed that this is an adequate assumption. Figure 7 shows the assumed base material model.

Four nonlinear elastic moduli, shown in Figure 8, were used to describe the subgrade properties. They are for the very soft, soft, medium, and stiff subgrades. These models had been successfully used before ILLI-PAVE (4,10).

Table 2 gives a summary of the pavement material properties used in the analyses with ILLI-PAVE.

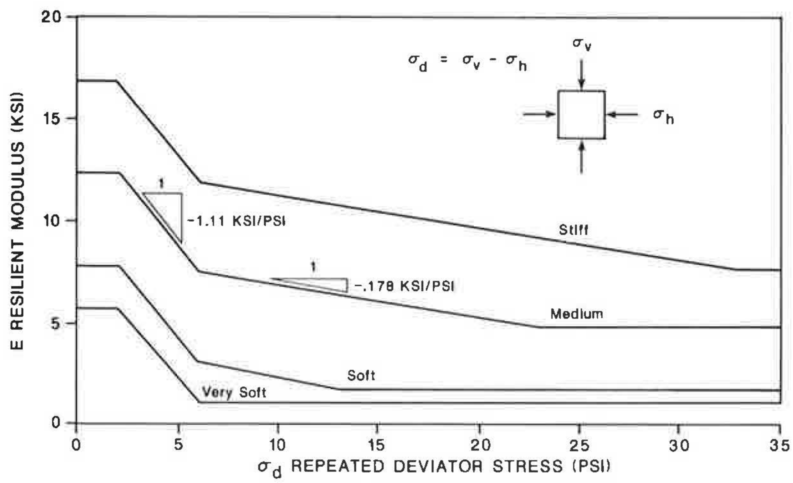



FIGURE 8 Subgrade soil material models.

TABLE 2 Material Properties Used in ILLI-PAVE

| Property | Surface Course | Base Course | Subgrade | | | |
|---|---|---|---|---|---|---|
| | | | Stiff | Medium | Soft | Very Soft |
| Unit weight (pcf) | 145.00 | 135.00 | 125.00 | 120.00 | 115.00 | 110.00 |
| Lateral pressure coefficient at rest | 0.87 | 0 60 | 0.82 | 0.82 | 0.82 | 0.82 |
| Poisson's ratio | | 0.38 | 0.45 | 0.45 | 0.45 | 0.45 |
| Unconfined compressive strength (psi) | | | 32.80 | 22.85 | 12.90 | 6.21 |
| Deviator stress (psi) | | | | | | |
| Upper limit | | | 32.80 | 22.85 | 12.90 | 6.21 |
| Lower limit | | | 2.00 | 2.00 | 2.00 | 2.00 |
| Deviator stress at breakpoint (psi) | | | 6.20 | 6.20 | 6.20 | 6.20 |
| Initial elastic modulus (ksi) | | | 12.34 | 7.68 | 3.02 | 1.00 |
| Elastic modulus at failure (ksi) | | | 7.605 | 4.716 | 1.827 | 1.00 |
| Constant elastic modulus (psi) | 30,000 | | | | | |
| Elastic modulus model | Linear | See Figure 12 | ← | See Figure 13 | | → |
| Friction angle (degrees) | | 40.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cohesion (psi) | | 0.0 | 16.4 | 11.425 | 6.45 | 3.105 |

### Generation of Deflection Basin Using ILLI-PAVE

To obtain enough load deflection data to cover a wide spectrum of light pavement structures with different materials, a series of finite element computer runs was made. These simulations included a combination of four subgrade types, that is, very soft, soft, medium, and stiff, and four base course material types with $K_1$-values of 10,000, 100,000, 200,000, and 300,000. In addition, four different base course thicknesses were used: 2, 6, 12, and 18 in. For all of these combinations, four FWD loadings of 80, 100, 140, and 200 psi were used. The corresponding loads were 8,765, 10,956, 15,339, and 21,913 lb. In addition to this framework, other combinations were used as necessary. The results of these simulations were found to form a more than adequate pool of data from which important correlations of various parameters were identified.

### Matching the Measured Deflection Basin Using ILLI-PAVE

Previous study (6) had shown ILLI-PAVE to be adequate in predicting the response of flexible pavement to loads. That presupposes that appropriate material models are used to simulate the response of real pavements.

In this study, measured deflection basins of farm-to-market road sections were successfully matched to show further that the program and the material models used in it are valid. The procedure was to adjust the input for subgrade and base course material characteristics to obtain field-measured deflection basins. Some difference in the curvature of the deflection basin was observed and was probably due to the lack of homogeneity of the base and the subgrade materials. Table 3 gives the results obtained for two of the sections that were matched.

### Load Deflection Model

A hyperbolic relationship between the load and the deflection of the light pavement structure was assumed. Because the hyperbolic stress-strain relationship is true of most soil materials (12-14) and because the light pavement structures considered are composed of soil materials, it is reasonable to adopt this as the load deflection model. The general equation is

$$P = \Delta/(A + B\Delta) \tag{2}$$

where

P = load and
Δ = deflections.

The constants A and B will hereafter be termed coefficient A and coefficient B.

Rewriting Equation 2 results in

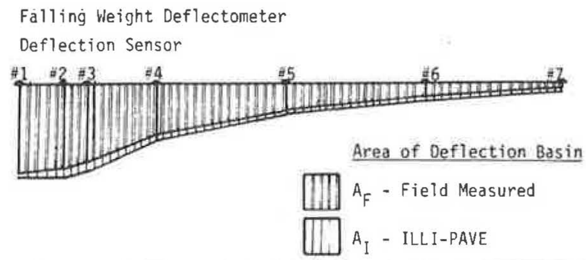
$$\Delta/P = A + B\Delta \tag{3}$$

A plot of Δ/P versus Δ yields the straight line, shown in Figure 9, from which coefficients A and B are found. Equation 3 assumes a stress-softening behavior. However, extrapolation of field-measured maximum deflections for different loads showed that some pavements do stress harden. To allow for this, a modified hyperbolic load deflection equation was used. This expression is

$$P/\Delta = (1/A) + (1/C)P \tag{4}$$

where C is a constant.

**TABLE 3 Comparisons of Measured Deflection Basins with ILLE-PAVE Results**




| ROAD | FM50 | | FM3058 | |
|---|---|---|---|---|
| MILEPOST | 12 | | 10 | |
| SECTION | 2 | | 1 | |
| FWD LOAD (LBS) | 11473 | | 11140 | |
| DEFLECTION (MILS) | Field | ILLI-PAVE | Field | ILLI-PAVE |
| @ SENSOR NO. 1 | 26.57 | 26.99 | 55.75 | 55.60 |
| 2 | 19.45 | 22.57 | 44.61 | 43.53 |
| 3 | 16.02 | 19.96 | 33.50 | 35.70 |
| 4 | 10.12 | 4.80 | 15.59 | 18.37 |
| 5 | 4.57 | 2.40 | 5.71 | 5.72 |
| 6 | 2.40 | 2.15 | 3.54 | 2.67 |
| 7 | 2.17 | 1.58 | 2.74 | 2.07 |
| RATIO OF $A_I/A_F$ | 1.07 | | 1.01 | |
| MEASURED BASE COURSE THICKNESS (INS) | 13.5 | | 7.5 | |
| BASE COURSE MODEL WHERE θ = DEVIATOR STRESS (PSI) | $15000\theta^{0.60}$ | | $20000\theta^{0.33}$ | |
| SUBGRADE MODEL | soft | | very soft | |

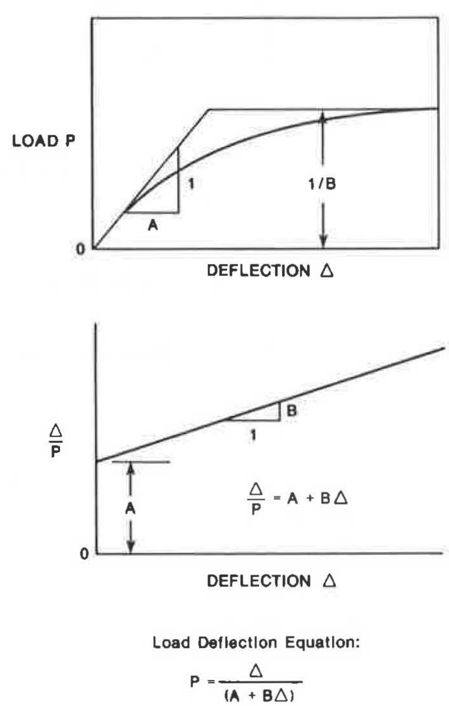



**FIGURE 9 Load deflection model—stress-softening form.**

A plot of P/Δ versus P yields a straight line as shown in Figure 10 from which A and C are found. Careful examination of the hyperbolic equation shows that by putting B = -A/C into Equation 2, a stress-hardening form of load deflection behavior results. Henceforth, these expressions are described as the stress-hardening and the stress-softening form of the hyperbolic load deflection equation for the pavements considered.

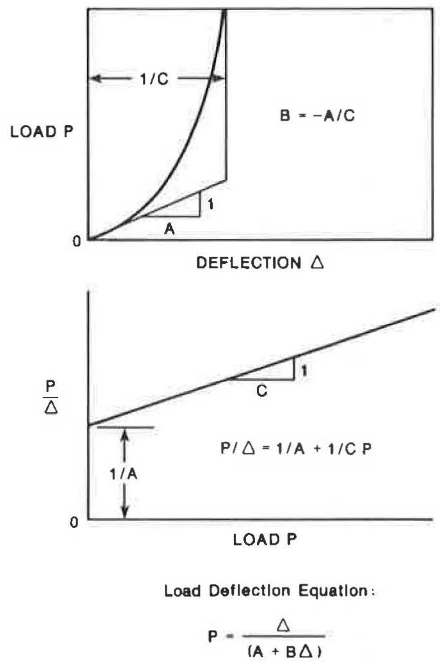



FIGURE 10 Load deflection model–stress-hardening form.

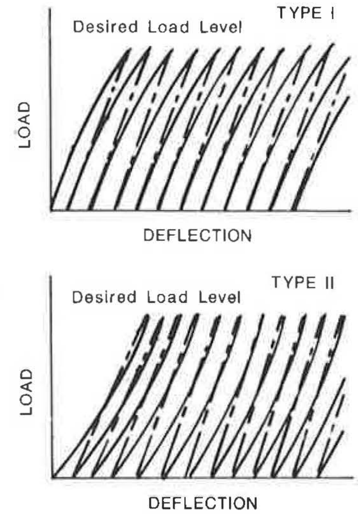



FIGURE 11 Load deflection model for repetitive loading (rutting) on pavement.

### Load Rating and Rutting Model

A rut can be formally defined as (15) "a permanent deformation in and of the pavement layers or subgrades caused by consolidation or lateral movement of the materials due to traffic loads." Because the farm-to-market roads being considered do not contain much thickness of asphaltic material to move laterally under loads, rutting due to consolidation is the primary concern.

In considering the problem of rebound deformation under repetitive loading, the following information is of some relevance. In the loading and reloading of silica sand, Duncan and Chang (12) found that after the initial loading, the path of which was hyperbolic, the unloading and reloading path could be approximated with a high degree of accuracy as linear and elastic. In another study, Raad and Figueroa (16) observed that the resilient behavior of granular base and subgrade were maintained even after large deformations. Larew and Leonards (17) suggested that the rebound reached an equilibrium value after approximately 1,000 repetitions. Thompson and Robnett (18) thought that the size of the rebound was related to the moisture level.

For the purpose of developing a load rating model, the rutting models shown in Figure 11 were assumed. The Type I model shows a stress-softening load deflection behavior and the Type II a stress-hardening one. The unloading path was assumed to be linear. This path is expressed, using a multiplier, in terms of the initial slope or initial stiffness of the pavement. The multiplier is assumed to be independent of the load level and can be found if information about the measured rut depth caused by a known number of passes of a certain load is available. By using measured rut depths and the corresponding number of 18-kip equivalent single axle loads (ESALs) on farm-to-market roads obtained from a previous Texas Transportation Institute project (19), estimated values for the multiplier can be obtained. These are found to depend on the initial stiffnesses of the pavements, as will be shown later.

## SUMMARY OF RESULTS

### Description and Discussion of Load Rating Procedure

Two approaches to the load rating procedure were developed. One is for use with a falling weight deflectometer and the other, which is based on the first, is for use with a Dynaflect. The two approaches are presented in depth in the following sections. Although they are described as if all of the data reduction is done by hand, the entire process has been programmed and is done automatically.

### Procedure Using the Falling Weight Deflectometer

1. Obtain the field-measured response of pavement to an FWD pressure of about 100 psi that corresponds to a load of about 10,956 lb. This loading will be referred to as the standard FWD load. The condition is necessary because much of this procedure was developed on the basis of that load level.
2. Adjust measured deflections at Sensors 1 and 7 to their equivalent values at the standard FWD load. This can be done by multiplying the values by the ratio of 10,956 lb over the registered load transmitted to the pavement. A linear variation can be assumed because the departure is not expected to be large. These corrected deflections will be referred to as the FWD deflections in the rest of the procedural outline.
3. Determine coefficient A of the load deflection equation. The stiffness of a pavement structure refers to the value obtained by dividing the applied load by the corresponding deflection at the point of loading. The overall stiffness is then the division

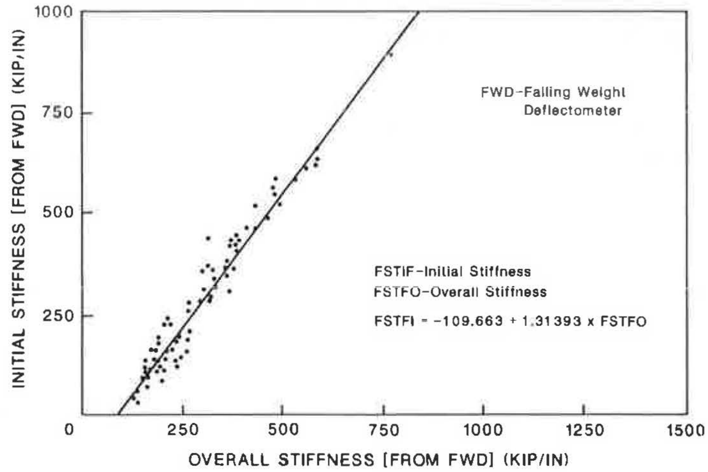



**FIGURE 12** Determination of initial slope (stiffness) of load deflection curve.

of the standard FWD load by the maximum FWD deflection, which will be at Sensor 1. The initial stiffness, which is the slope of the load deflection curve near a zero load, is then read from Figure 12 and the inverse of this is the value of coefficient A. Figure 12 was derived from field-measured deflections.

4. Determine the type of subgrade. With the FWD deflection at Sensor 7, from Figure 13, the type of subgrade soil model can be determined. Figure 13 was based on field-measured deflections.

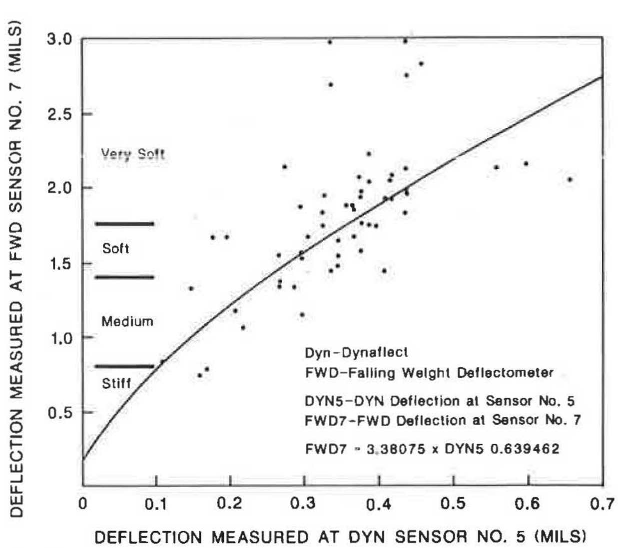



**FIGURE 13** Determination of subgrade soil model from deflection.

5. Determine the standard deflection. This is the maximum deflection that will be obtained if the particular pavement structure is resting on a very soft subgrade and loaded with a standard FWD load. This value can be obtained from Figure 14. This correlation was derived from the ILLI-PAVE analyses and was found to match the field-measured values.

6. Determine the base course material model. By interpolating from the curves shown in Figure 15, the $K_1$-value of the base course material can be

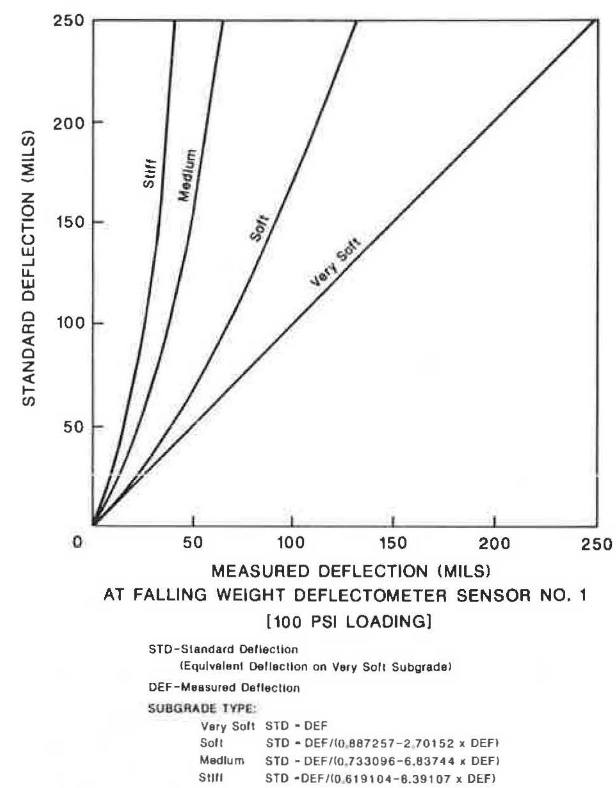
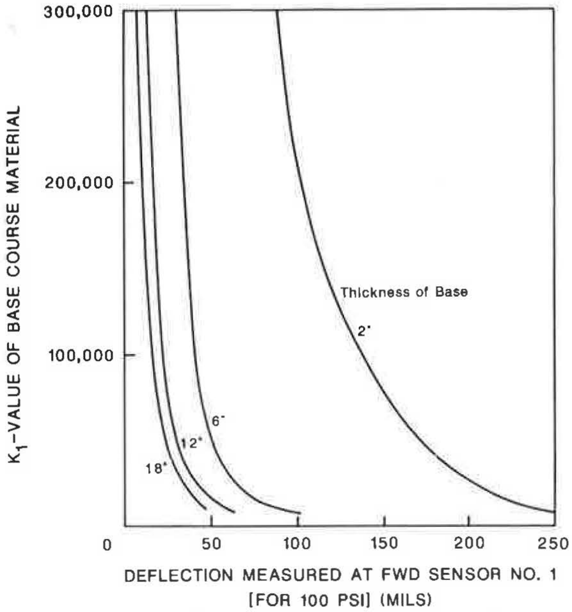



**FIGURE 14** Determination of standard deflection.

found. Necessary inputs will be the base course thickness and the FWD deflection at Sensor 1. These curves were based on the ILLI-PAVE analyses.

7. Determine coefficient B of the load deflection equation. As can be seen from Figure 16, coefficient B is dependent on the $K_1$-value of the base course material and the subgrade type. The positive value can be interpolated from the curves shown in the figure. Difference scales for the value of coefficient B are given to adjust for the different subgrades encountered. This figure was based on ILLI-PAVE analyses. For the negative value of coefficient B, refer to Figure 17. This value is a linear function of the value of coefficient A of the load de-




FWD-Falling Weight Deflectometer
STD-Standard Deflection
H-Base Course Thickness (ins)

$K_1 = CC \times STD^{CD}$

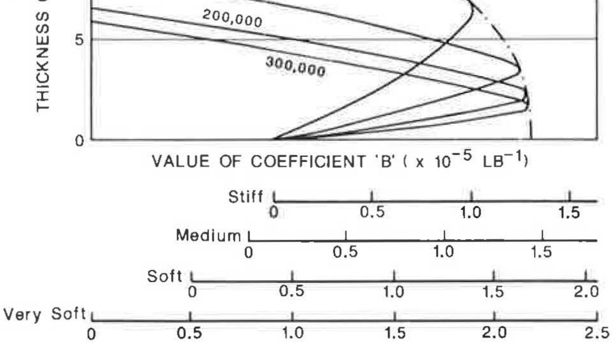
For $H \geq 5.0$ $CC = 10^{12.8778H^{-0.18345}}$

$CD = -2.95407e^{-0.017531H}$

For $H < 5.0$ $CC = 10^{16.1791H^{-0.349993}}$

$CD = -4.98760H^{-0.39432}$

**FIGURE 15** Determination of base course material model from FWD deflection.




B-Coefficient 'B' of Load Deflection Equation
H-Thickness of Base Course
$K_1$-Coefficient for Base Course Material Model

$B = CE + CF \times H + CG \times H^2$

where $CE = 1.36543 \times 10^{-6} \times K_1^{0.185895}$

$CF = 3.15679 \times 10^{-6} + 3.24823 \times 10^{-11} \times K^1 - 1.05093 \times 10^{-16} \times K_1^2$

$CG = -1.74866 \times 10^{-7} + 1.00162 \times 10^{-11} \times K_1 + 2.3941 \times 10^{-17} \times K_1^2$

**FIGURE 16** Determination of positive value of coefficient B.

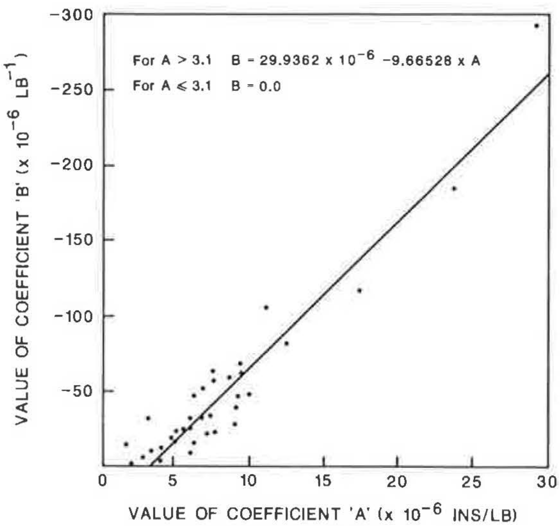



**FIGURE 17** Determination of negative value of coefficient B.

flection equation. As a check, it was observed that for a positive value of coefficient B, if the calculated maximum deflection differs from the measured value by more than 20 percent, it should be replaced with a negative value that can be found from Figure 17. This step was always found to provide a satisfactory load deflection equation. Figure 17 shows a linear relation between the negative values of coefficient B and coefficient A, both of which were calculated from measured deflections.

8. Determination of the multiplier for the initial slope. This multiplier when applied to the initial slope (stiffness) of the load deflection curve is the slope of the unloading path describing the deflection of the pavement after the passage of a wheel load. Sixty-four light pavement sections from five farm-to-market (FM) roads, namely FM 418 and FM 365 in District 20, FM 665 in District 16, FM 612 in District 8, and FM 1381 in District 13, were used to backcalculate this multiplier. Values of this multiplier from these sections were found to vary from about 0.90 to 1.7. Figure 18 shows a method of estimating this value. However, if the rut depth and the number of passes of a known load are available for a particular road, the multiplier can be backfigured from the equation

$$\text{Multiplier} = \Delta P_m \ [A\, P_m/(1 - B\, P_m)] - \Delta_m \tag{5}$$

where

$P_m$ = measured load and
$\Delta_m$ = measured rut depth and measured number of passes of $P_m$.

9. Determine the allowable number of passes. The number of passes of a desired load that will cause a specified rut depth can be easily found from the following expression:

$$N_x = R_x/[\Delta_N - (A\, P_{xi}/\text{Multiplier})] \tag{6}$$

where

$N_x$ = allowable number of passes of a load equal to $P_x$,
$R_x$ = specified rut depth,
$P_x$ = specified load, and
$\Delta_N = AP/(1 - BP_x)$.

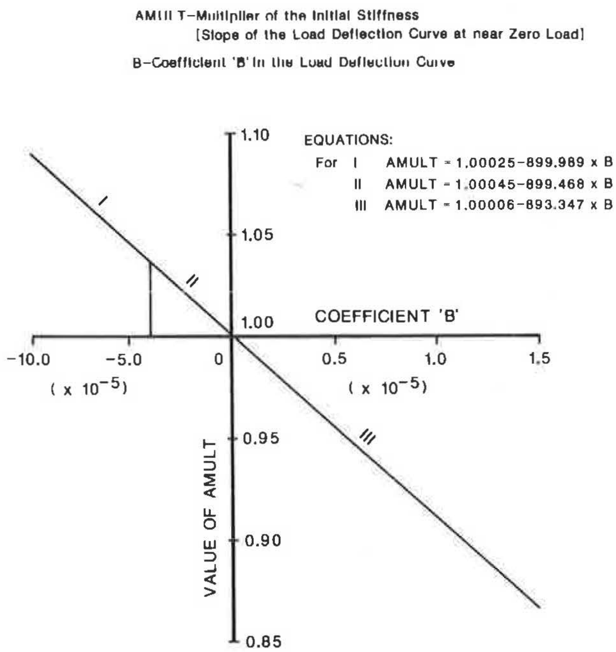



FIGURE 18 Determination of multiplier of the initial slope (stiffness) for the unloading path.

In the case of a set of different loads considered as a single pass, as for that of a multiple axle truck,

$$N_x = R_x / \left\{ \sum_{i=1}^{n} [\Delta_{N_i} - (A\,P_{xi}/\text{Multiplier})] \right\}$$

where n is the number of loads in the set.

Procedure Using the Dynaflect

1. Obtain field-measured response of pavement with a Dynaflect.

2. Determine the equivalent FWD deflection for the reading at Dynaflect Sensor 1. Because this approach is based on that described earlier for the FWD, the maximum Dynaflect deflection must be correlated with that of the FWD. Figure 19 shows the relationship between overall stiffness of pavement measured with a Dynaflect and that obtained from the FWD. The equivalent FWD deflection can be calculated from the following expression:

$$\text{FWD deflection} = -7.24474 + (29.6906 \times \text{Dynaflect deflection}) \quad (7)$$

3. Determine coefficient A of the load deflection equation. The equivalent FWD overall stiffness can be obtained from Figure 19. The initial stiffness, which is the slope of the load deflection curve near a zero load, is then read from Figure 12 and the inverse of this is the value of coefficient A.

4. Determine the type of subgrade. This is found from Figure 13 using the Dynaflect reading at Sensor 5.

The remainder of the procedure is identical to Steps 5 through 9 for the falling weight deflectometer.

Computer Program

A computer program, LOADRATE, written in FORTRAN, facilitates the load rating procedure developed in this study. This program can calculate the number of passes of a specified load that will cause a specified critical level of rut depth for every section for which a deflection basin is input and then give the average of the number of passes allowed for that particular road. The deflection basin can be that obtained using either a falling weight deflectometer or the Dynaflect. Figure 20 shows two computer outputs of a sample problem. It also is possible to print the material model of the base course and the subgrade for each section considered.

Evaluation of the Accuracy of the Procedure

In the correlation of data, regression analysis was used to get the best fit. The degree of accuracy of the simulated load deflection model can be seen in Figures 21-24. The figures compare the measured maximum deflections of the test sections with those obtained in the procedure at three different load levels using FWD readings. It can be seen that the best result was obtained at the 11,000-lb load level. This was because the material models for the

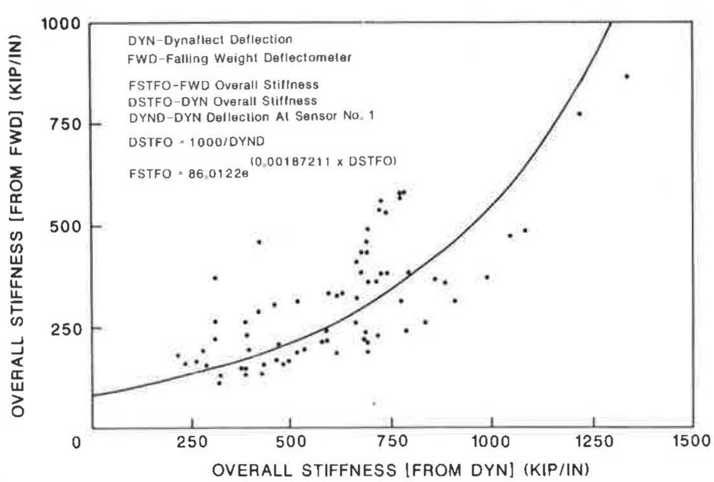



FIGURE 19 Determination of equivalent FWD overall stiffness from Dynaflect overall stiffness.

## Using the Falling Weight Deflectometer

TEXAS HIGHWAY DEPARTMENT
LOAD RATING OF LIGHT PAVEMENT

JOB:SAMPLE PROBLEM 1 TYPE 2-S1-2 VEHICLE

DISTRICT: 17 COUNTY:BURLESON ROAD:FM2000
ALLOWABLE RUT(INS): 0.75

| AXLE NUMBER | WHEEL LOAD(LBS) |
|---|---|
| 1 | 4000. |
| 2 | 9000. |
| 3 | 9000. |
| 4 | 9000. |
| 5 | 9000. |

RECORDED RUT(INS): 0.00 LOAD(LBS): 0. PASSES:0.0000D 00

DATE: 12/20/1982 FALLING WEIGHT DEFLECTOMETER

| SECTION NO. | BASE THICKNESS (INS) | DEFLECTIONS (MILS) W1 | W2 | W3 | W4 | W5 | W6 | W7 | LOAD (LBS) | NO. OF ALLOWABLE PASSES |
|---|---|---|---|---|---|---|---|---|---|---|
| 8- 0 | 7.00 | 54.88 | 32.91 | 21.18 | 10.31 | 5.04 | 2.87 | 2.17 | 11108. | 0.263D 03 |
| 8- 1 | 7.00 | 55.98 | 32.83 | 21.69 | 11.18 | 5.59 | 3.23 | 2.05 | 10981. | 0.233D 03 |
| 10- 0 | 7.00 | 51.93 | 32.83 | 22.44 | 11.65 | 5.00 | 2.44 | 1.20 | 11616. | 0.392D 03 |
| 10- 1 | 7.00 | 53.74 | 34.09 | 23.27 | 12.36 | 5.55 | 2.95 | 1.70 | 11696 | 0.350D 03 |
| 12- 0 | 6.00 | 31.53 | 19.29 | 13.54 | 7.21 | 4.02 | 2.60 | 1.30 | 11759. | 0.181D 04 |
| 12- 1 | 6.00 | 32.24 | 18.74 | 12.83 | 7.01 | 3.90 | 2.44 | 1.20 | 11791. | 0.170D 04 |

AVERAGE NUMBER OF PASSES TO CAUSE SPECIFIED RUT : 0.7908D 03

## Using the Dynaflect

DATE: 3/ 1/1983 DYNAFLECT

| SECTION NO. | BASE THICKNESS (INS) | DEFLECTIONS (MILS) W1 | W2 | W3 | W4 | W5 | NO. OF ALLOWABLE PASSES |
|---|---|---|---|---|---|---|---|
| 8- 0 | 7.00 | 2.13 | 1.53 | 1.14 | 0.87 | 0.60 | 0.287D 03 |
| 8- 1 | 7.00 | 1.89 | 1.50 | 1.14 | 0.86 | 0.66 | 0.456D 03 |
| 10- 0 | 7.00 | 1.41 | 1.08 | 0.74 | 0.55 | 0.39 | 0.386D 04 |
| 10- 1 | 7.00 | 1.47 | 1.14 | 0.74 | 0.53 | 0.35 | 0.161D 04 |
| 12- 0 | 6.00 | 3.30 | 1.14 | 0.78 | 0.54 | 0.22 | 0.958D 02 |
| 12- 1 | 6.00 | 1.47 | 1.08 | 0.78 | 0.54 | 0.40 | 0.168D 04 |

AVERAGE NUMBER OF PASSES TO CAUSE SPECIFIED RUT : 0.1332D 04

**FIGURE 20 Computer printout for a sample problem.**

base course and the subgrade were determined on the basis of a 100-psi loading from an FWD. At the 24,000-lb load level the deviations were more pronounced. At a lower load level the load deflection curve appears to closely match that obtained from the field data. It should be noted that the procedure presented uses only one deflection basin. The accuracy of the approach using the FWD is an indication of the accuracy of the approach using the Dynaflect because the latter was based on the former.

When evaluating the accuracy of the rutting model, it was observed that the analysis is quite sensitive to the value of the slope multiplier. Backcalculation of the number of passes for those sections used to derive the expression for the multiplier showed that, for certain cases, only the order of magnitude could be reproduced. This might be avoided if some rut history were available to compute the multiplier.

### Sample Problem

To illustrate the use of this procedure in load rating light pavements, Figure 25 shows the results of the analysis with various types of trucks. Vehicles with weights at the current legal limits in Texas are compared with those proposed (20). It can be seen that the number of passes of a particular vehicle that will cause a certain rut depth, in this case 0.75 in., depends more on the load distribution on the axles than on the gross vehicle weight. Hence

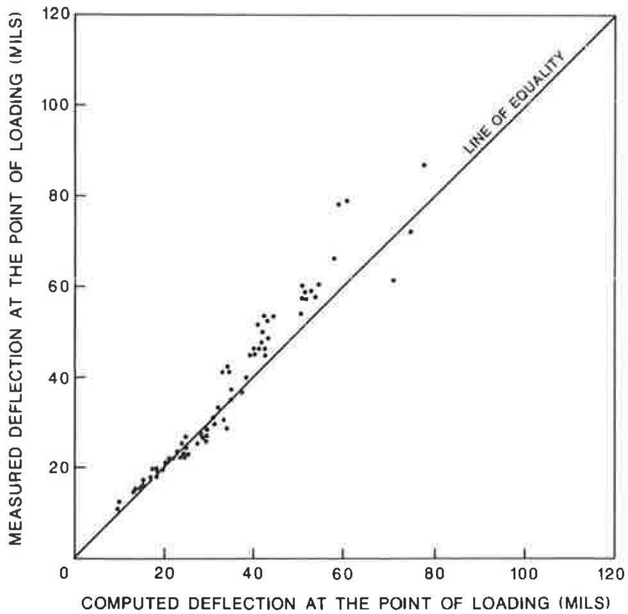



FIGURE 21 Comparison of measured deflections with computed deflections at about 9,000 lb loading.

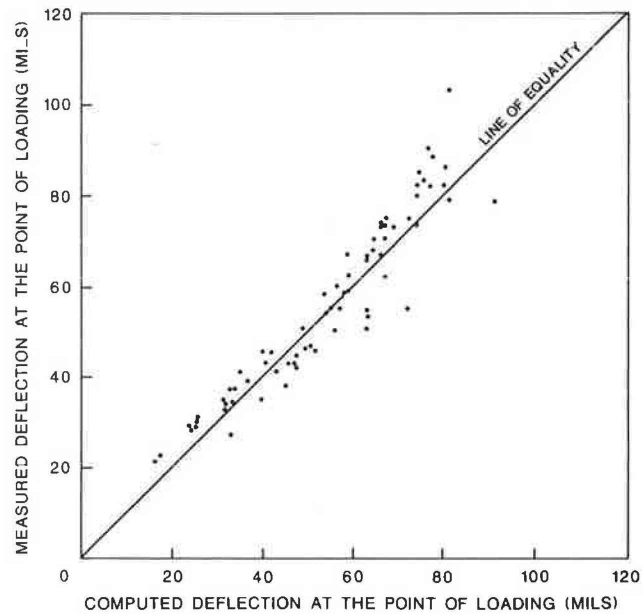



FIGURE 23 Comparison of measured deflections with computed deflections at about 15,000 lb loading.

it can be seen that, when a criterion or basis for measuring the level of damage is decided on, the procedure can be used as a tool for evaluation.

## SUMMARY AND CONCLUSIONS

A new procedure for the load rating of light pavement structures using the falling weight deflectometer or the Dynaflect has been presented. A computer program was developed. In the course of the study, the following conclusions were drawn:

1. It was found that light pavement structures, such as those commonly found in the farm-to-market roads, show either a stress-softening form or a stress-hardening form of load deflection behavior.
2. It was shown that a hyperbolic stress-strain relationship or load deflection may be used to describe both the stress-softening and the stress-hardening form of load deflection characteristics of light pavements.
3. The ILLI-PAVE finite element pavement analysis program was again verified and shown capable of simulating deflection basins of flexible light pavement structures to match those measured in the field.
4. A procedure for determining the nonlinear elastic material models for the base course and the subgrade using the falling weight deflectometer or the Dynaflect was developed.

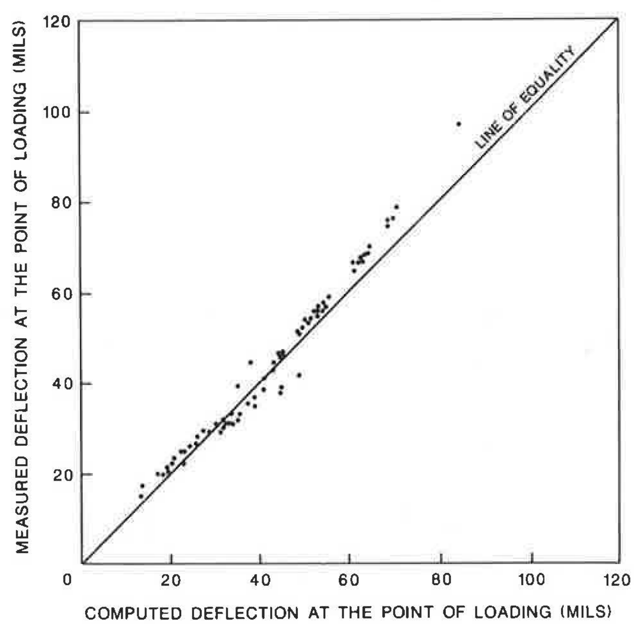



FIGURE 22 Comparison of measured deflections with computed deflections at about 11,000 lb loading.

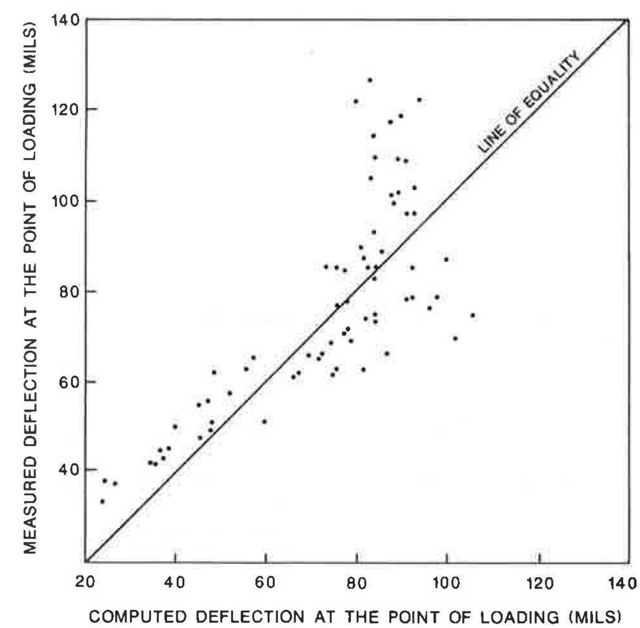



FIGURE 24 Comparison of measured deflections with computed deflections at about 23,000 lb loading.

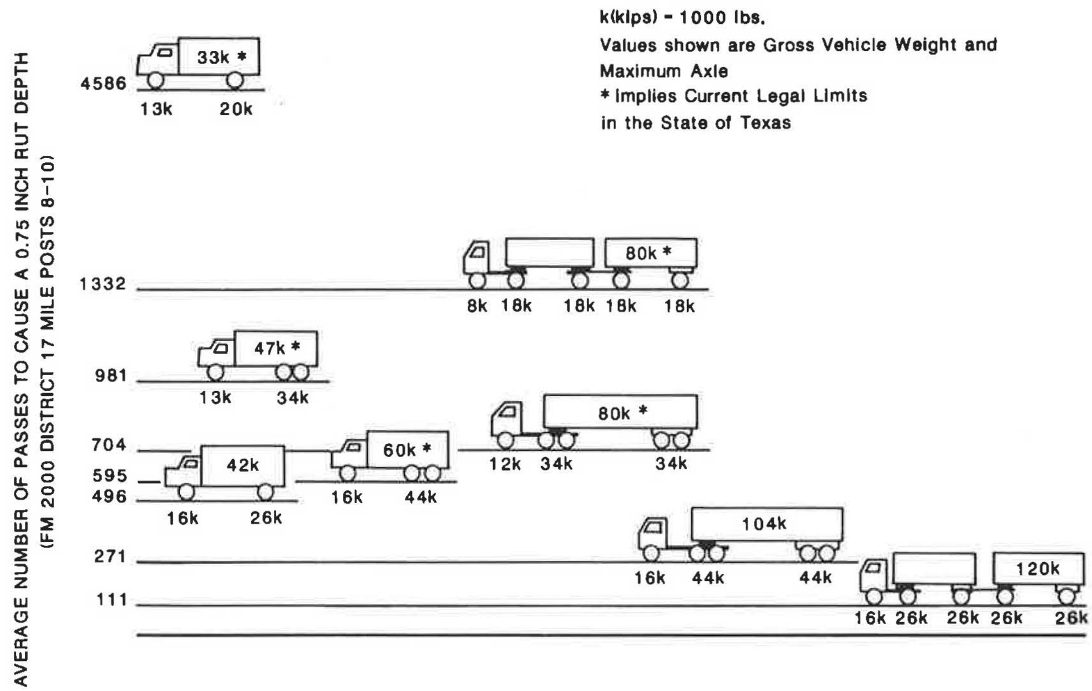



FIGURE 25 Comparison of damage that can be done by various overweight vehicles on a farm-to-market road.

5. A model of repetitive loading on pavements, which assumes a hyperbolic-shaped load deflection curve with a linear unloading path, was proposed. The slope of this unloading line was found to be smaller than the initial slope of the load deflection curve for the stress-softening type of pavement, but it was larger for the stress-hardening type.

6. Pavements with a thicker base course were usually found to show a stress-hardening form of load deflection behavior. This form is more resistant to rutting than is the stress-softening form.

7. It was shown that the proposed procedure is capable of reproducing the load deflection characteristics of the pavement sections tested.

8. The procedure calculates realistic rut depth histories for a variety of different vehicles.

## ACKNOWLEDGMENT

This research was conducted in cooperation with the Federal Highway Administration, U.S. Department of Transportation. The authors are grateful for the funding support provided by the Texas State Department of Highways and Public Transportation under Research Project 2-8-80-284.

## REFERENCES

1. R.C. Koole. Overlay Design Based on Falling Weight Deflectometer Measurements. In Transportation Research Record 700, TRB, National Research Council, Washington, D.C., 1979, pp. 59-72.
2. Dynatest 8000 FWD Test System. Dynatest Consulting, Inc., Ojai, Calif., 1982.
3. F.H. Scrivner, G. Swift, and W.M. Moore. A New Research Tool for Measuring Pavement Deflection. In Highway Research Record 129, HRB, National Research Council, Washington, D.C., 1966, pp. 1-11.
4. J.L. Figueroa and M.R. Thompson. Simplified Structural Analysis of Flexible Pavements for Secondary Roads Based on ILLI-PAVE. In Transportation Research Record 766, TRB, National Research Council, Washington, D.C., 1980, pp. 5-10.
5. ILLI-PAVE User's Manual. Transportation Facilities Group, Department of Civil Engineering, University of Illinois at Urbana-Champaign, May 1982.
6. M.L. Taylor. Characterization of Flexible Pavement by Non-Destructive Testing. Ph.D. dissertation. University of Illinois at Urbana-Champaign, 1978.
7. J.M. Duncan, C.L. Monismith, and E.L. Wilson. Finite Element Analysis of Pavements. In Highway Research Record 228, HRB, National Research Council, Washington, D.C., 1968, pp. 18-33.
8. E.G. Klegn, J.H. Maree, and P.F. Savage. The Application of a Portable Pavement Dynamic Cone Penetrometer to Determine in-situ Bearing Properties of Road Pavement Layers and Subgrades in South Africa. Proc., 2nd European Symposium on Penetration Testing, Amsterdam, The Netherlands, May 24-27, 1982, pp. 277-283.
9. W.A. Dunlap. Deformation Characteristics of Granular Materials Subjected to Rapid, Repetitive Loading. Research Report 27-4. Texas Transportation Institute, Texas A&M University, College Station, Nov. 1967.
10. M.S. Hoffman and M.R. Thompson. Backcalculating Nonlinear Resilient Moduli from Deflection Data. In Transportation Research Record 852, TRB, National Research Council, Washington, D.C., 1982, pp. 42-51.
11. E.J. Yoder and M.W. Witczak. Principles of Pavement Design. John Wiley & Sons, Inc., New York, 1975.
12. J.M. Duncan and C.Y. Chang. Nonlinear Analysis of Stress and Strain in Soils. Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 96, No. SM5, pp. 1629-1653.
13. R.L. Kondner. Hyperbolic Stress-Strain Re-

sponse: Cohesive Soils. Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 89, No. SM1, pp. 115-148.
14. R.L. Kondner. A Hyperbolic Stress-Strain Formulation for Sands. Proc., 2nd Pan-American Conference on Soil Mechanics and Foundation Engineering, Brazil, Vol. 1, 1963, pp. 289-324.
15. R.E. Smith, M.I. Darter, and S.T. Herrin. Highway Distress Identification Manual. Interim Report. FHWA, U.S. Department of Transportation, March 1979.
16. L. Raad and J.L. Figueroa. Load Response of Transportation Systems. Journal of the Transportation Engineering Division, ASCE, Vol. 106, No. TE1, 1980, pp. 111-128.
17. H.G. Larew and G.A. Leonards. A Strength Criterion for Repeated Loads. Proc., HRB, National Research Council, Washington, D.C., 1962, pp. 529-556.
18. M.R. Thompson and Q.L. Robnett. Resilient Properties of Subgrade Soils. Transportation Engineering Journal, Jan. 1979, pp. 71-89.
19. J.P. Mahoney and R.L. Lytton. Measurements of Pavement Performance Using Statistical Sampling Techniques. Research Report 207-2. Texas Transportation Institute, Texas A&M University, College Station, March 1978.
20. C.M. Walton, C-P. Yu, P. Ng, and S. Tobias. An Assessment of Recent State Truck Size and Weight Studies. Research Report 241-4. Center for Transportation Research, University of Texas at Austin, July 1982, pp. 113-116.

Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.

# In Situ Pavement Moduli from Dynaflect Deflection

SHAKIR HUSAIN and K. P. GEORGE

ABSTRACT

A complete pavement evaluation entails not only a condition survey, including load testing, but also in situ material characterization. With the simplifying, but justifiable, assumption that pavement materials are elastic under moving wheel loads, they are characterized by a modulus and Poisson's ratio. This study develops a methodology and computer program to determine the in situ elastic modulus for each layer in a multilayer flexible pavement. The surface deflection basin measured using the Dynaflect, or similar devices that employ five or more deflection sensors, would be the primary input data in the program. Points on a two-dimensional surface deflection basin are fitted to field data. Iteration is required to match the measured with the computed points by adjusting the assumed values for the layer moduli. The Chevron program is used to predict deflections. A computerized pattern search technique, the mainstay of the iteration, accomplishes the task of matching the deflections by minimizing the sum of squared errors. The usefulness of the method is illustrated by comparing the outputs of this program with those of the "standard" OAF program developed for FHWA. Results are presented to show that the present method gives far more reasonable results than does the OAF program. Suggestions for improving the solution procedure when dealing with erratic or inconsistent deflection readings, or both, are discussed. The feasibility of using deflection data of other devices, for example falling weight deflectometer, in the present method is illustrated by example problems.

A pavement undergoes deterioration with time and traffic; therefore, rehabilitation or even reconstruction is required to extend its useful life. In situ structural strength (i.e., remaining life of existing pavement), if properly evaluated and accounted for in the design procedure, aids in reducing rehabilitation construction expenses. A complete structural evaluation may determine the adequacy of the pavement and enables the engineer to predict its future service life with respect to the traffic using it. When pavement is found to be inadequate, the evaluation forms the basis for designing the improvements needed to provide service for a selected design period.

It is both useful and relevant for an engineer to have knowledge of the inherent mechanical properties of a pavement structure in order to calculate various responses (stresses and strains) throughout the