Typical Curves for Evaluation of Pavement Stiffness from Dynaflect Measurements

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ABSTRACT

Currently, no direct solution exists that provides the pavement in situ layer moduli from deflection measurements. Current methods evaluate the pavement layer moduli from deflection measurements by using either empirical approaches or static layered elastic computer programs with iterative solutions. In this study, mechanistically based typical curves and tables are developed to evaluate the moduli of the four highway pavement layers--surface, base, subbase, and subgrade--from the Dynaflect measurements based on both static and dynamic analyses. The curves and tables are developed by using the Chevron computer program for the static analysis and the DYNAMIC computer program for the dynamic analysis. The results are applicable to a large number of typical combinations of layer thicknesses and material moduli. If the layer thicknesses are known and the Dynaflect measurements are determined, the four moduli of the pavement layers can be evaluated. The curves and tables developed are simple to use, without the need for previous empirical relationships or computer analysis. The study demonstrates that the static and dynamic predictions of the layer moduli are different in most cases. However, the research technique used in this study needs field verifications or other independent validation procedures to support the obtained results.

The rational rehabilitation of rapidly deteriorating highway pavements requires knowledge of the stiffness of existing pavements. Nondestructive testing (NDT) is being widely used to evaluate the load-carrying capability of pavements. Unlike laboratory testing, NDT is fast and accurate and can provide the in situ layer moduli with a minimum of disturbance and cost.

The nondestructive evaluation of pavements generally follows one of two main techniques: wave propagation or surface deflection measurements. The deflection measurement tests have been extensively used by many highway agencies because of their simplicity and their ability to model real traffic load intensities and durations. Therefore, the layer moduli computed from surface deflection measurements are more nearly representative of field conditions.

One of the most widely used deflection measurement devices is the Dynaflect, which applies a steady-state harmonic load with a peak-to-peak load of 1,000 lb and a frequency of 8 Hz. The force is transmitted to the pavement through two 4-in.-wide steel wheels with a 16-in. outside diameter, spaced 20 in. apart. The peak-to-peak deflections are measured by using five deflection sensors (geophones) located midway between the two steel wheels and at four other locations 1 ft apart, as shown in Figure 1.

Different modes of loading (static, harmonic, transient, etc.) result in different deflection measurements for the same load intensities (1-3), as shown in Figure 2. The pavement response is highly dependent on the mode of loading, load frequency, or both as shown in Figure 3. To date, most methods of analysis treat different modes of loading identically. The dynamic analysis has recently been applied to pavement response to deflection measurement devices in several studies (4-8). These studies indicate that the dynamic response of pavement may be significantly different from the static response because of the inertia of the pavement system. Because the Dynaflect applies loads with an 8-Hz frequency, a resonant condition might occur if the natural vibration frequency of the pavement structure is close to that frequency. In this case, the pavement deflection is magnified and, unless the dynamic analysis is used, the interpretation of results may be misleading.

The first step in the evaluation process is the estimation of the layer moduli, after which a decision is made to determine the required overlay thickness based on previous field correlations. No direct theoretical solution is currently available to evaluate the layer moduli if the surface deflections and the layer thicknesses are known. In the current techniques, iterative solutions are used in which initial estimates of the moduli are assumed and the corresponding surface deflections are computed. The estimated moduli are then adjusted to improve the fit between the computed and the measured deflections.

Although this method provides a reasonable degree of accuracy, it requires use of a computer, which may not be accessible, and the experience to use it, which may not be available. Also, because the layer moduli are sensitive to deflection measurements and any iteration procedure allows a certain amount of tolerance, the resulting solution is not unique. In addition, all the commonly available multilayer computer programs are based on static analyses that do not match the dynamic loads applied by NDT devices.

Typical curves were recently developed to estimate the layer moduli from surface deflections by using the static method of analysis (9). The objective of this study was to provide typical curves and tables to enable the highway engineer to estimate the in situ moduli of pavement layers from surface deflections by using the dynamic analysis. The curves

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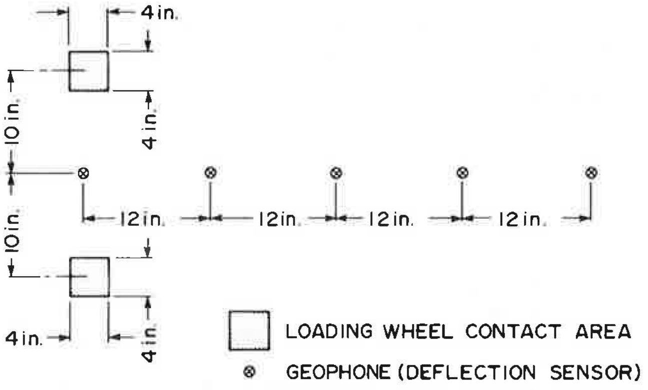

FIGURE 1 Location of Dynaflect loading wheels and geophones.

and tables can be easily used with an acceptable degree of accuracy, without the need for using the computer. Moreover, the static solution can also be obtained by using these curves and tables, and a comparison between the static and the dynamic predictions can be made.

ASSUMPTIONS

In this study, the pavement structure is assumed to consist of four layers: surface, base, subbase, and subgrade. The materials are idealized to be homogeneous, isotropic, and linear elastic or viscoelastic. Thus, the material of each layer is characterized by Young's modulus, Poisson's ratio, mass density, and material damping ratio. Further, the analysis assumes existence of laterally unbounded soil and pavement layers, underlain by a rigid bedrock at a finite depth. Full interface bonding (no slip) conditions are assumed at the layer interfaces.

NONLINEARITY AND STRESS SENSITIVITY

For many years it has been known that the subgrade material is nonlinear. However, if the load is repeated several times, the effect of nonlinearity is reduced. For example, Figure 4 shows a typical stress-strain relationship for a soil specimen subjected to a triaxial state of stress in which the axial stress is varied in a pulsating form while the confining pressure is kept constant. It can be observed that the nonlinearity is apparent when the

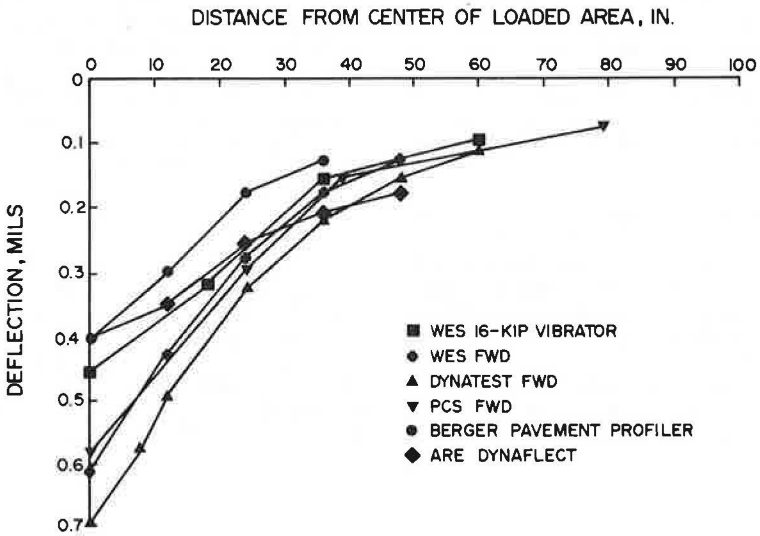

FIGURE 2 Deflection measurements of six NDT devices as a flexible airport pavement normalized to 1,000-lb force level *(2)*.

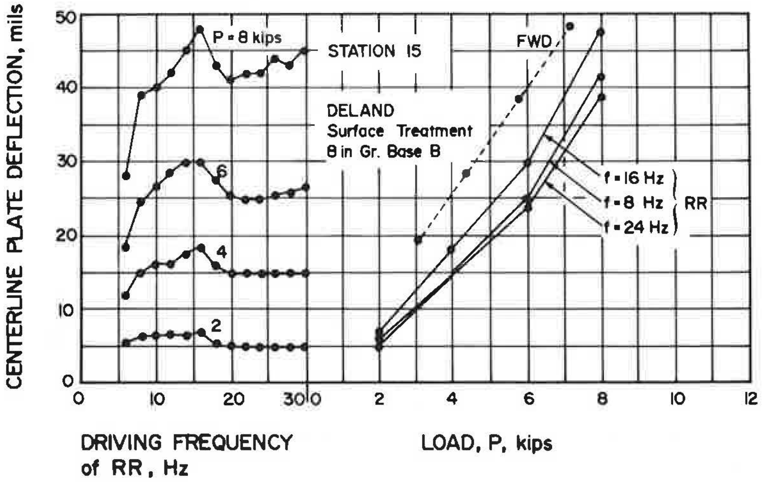

FIGURE 3 Road Rater 2008 and falling weight deflectometer data *(3)*.

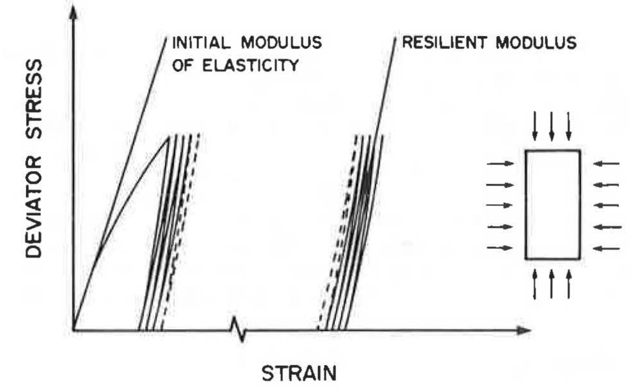

FIGURE 4 Definition of resilient modulus.

load is applied for the first time, after which the material can be assumed to be linear without significant error.

In Figure 4, the initial slope of the curve when the load is applied for the first time can be defined as the initial modulus of elasticity, or initial Young's modulus. The deviator stress divided by the recoverable strain is defined as the resilient modulus, as represented by the slope of the second line in Figure 4. Therefore, the resilient modulus is the modulus of the material after many load repetitions at which the effect of nonlinearity becomes small. This indicates that if a repeated type of load is applied, the resilient modulus can be used instead of Young's modulus in a linear analysis with a reasonable approximation.

On the other hand, the stress-strain relationship is affected by the state of stress of the material. However, when the load is applied several times, the resilient modulus does not change considerably when the state of stress is changed. For example, Figure 5 shows a typical stress-deflection diagram from repetitive plate load testing on a subgrade material according to ASTM test procedure D1195 (10). It is shown in this figure that the stress divided by the recoverable deflection is almost constant regardless of the applied stress level. According to the Boussinesq solution for one-layer systems (11),

$$\Delta = pa/E(F) \tag{1}$$

or

$$E = (p/\Delta)aF$$

where

Δ = deflection,
p = stress,
a = radius of plate,
E = Young's modulus,
F = a factor that is a function of z/a and r/a,
z = depth of the point of interest, and
r = lateral distance between load and the point of interest.

Thus, if p/Δ is almost constant for repeated loads at different stress levels, the modulus of the material remains approximately constant.

It should be noted that laboratory resilient moduli obtained for soil samples subjected to triaxial states of stress (AASHTO T274) vary at different confining pressures. This change of resilient modulus with change in confining pressure appears to contradict the previous field results shown in Figure 5. This contradiction, however, is expected because the confining pressure in the laboratory test is usually kept constant when the axial load is changed, whereas the stresses in the three orthogonal directions are simultaneously changed when the load is applied in the field.

METHOD OF ANALYSIS

The dynamic solution used in this study is based on the Helmholtz equation, which is the governing equation for steady-state elastodynamics (12). Because no exact solution to this equation is available for harmonic loadings applied on a multilayered system, a simplified numerical solution is used (13). It is assumed in this solution that the displacement fields

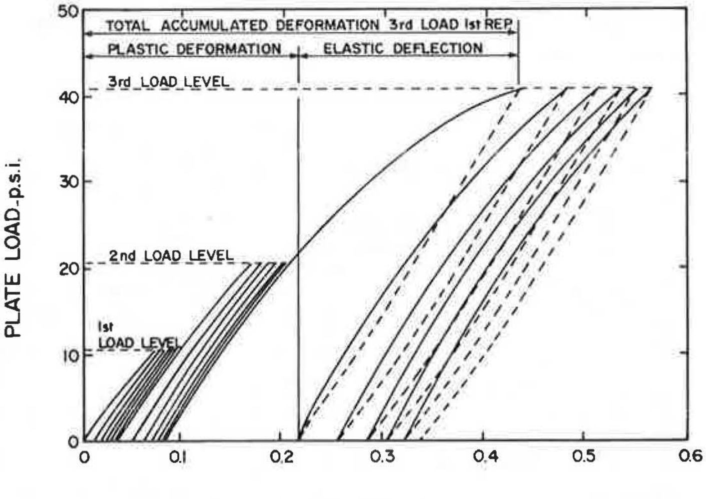

FIGURE 5 Typical load-deflection diagram from repetitive plate load testing (10).

vary linearly (in the direction of layering) between adjacent interfaces. Therefore, it is important that sufficiently thin artificial sublayers be specified in order to preserve accuracy. The dynamic solution is developed in the computer program DYNAMIC (13).

The input data required in the computer program are number of layers (and sublayers), layer thicknesses, depth to bedrock, mass densities, Young's moduli, Poisson's ratios, and material damping ratios representing the viscous effect. The computer program also requires information on diameter of the load plate, location of the load with respect to various layers, frequency of loading, and locations where results are required. The current version of the program is capable of computing the in-phase and out-of-phase deflections in the vertical, radial, and tangential directions at any location throughout the pavement system. Because the solution assumes linear material behavior, the results are obtained due to a load intensity of 1 psi. Further, the DYNAMIC program with zero load frequency was checked versus the Chevron program under identical conditions; it was found that it provided the same results.

Note that the bedrock reflects the waves generated by the dynamic excitations, and consequently the pavement response is influenced by the depth to bedrock. However, in the static analysis the depth to bedrock is not as significant as it is in the dynamic analysis. Also, the density is not required in the static analysis to characterize the materials because the inertial effect is ignored.

To simulate the load applied by the Dynaflect, an 8-Hz harmonic load is assumed to be uniformly distributed on a circular area of 16 in.^2 at the pavement surface. The vertical deflections are computed at distances of 10.0, 15.6, 26.0, 37.4, and 49.0 in., representing various geophone locations. Because the loads on the two wheels are simultaneous, the response due to the two wheels can be obtained by superposition. By using this load representation, two minor approximations are made. The first approximation is the assumption that the contact areas are circular instead of rectangular, and the second approximation is the use of uniformly distributed loads instead of rigid wheels. The errors resulting from these two approximations are small, particularly away from the load.

DEVELOPMENT OF TYPICAL CURVES AND TABLES

A number of typical curves and tables are developed in this study to aid the highway engineer in evaluating the in situ pavement moduli from the Dynaflect deflection data. The Chevron computer program was used to evaluate the surface deflections for a wide range of layer thicknesses and moduli combinations due to a load intensity of 1 psi. Typical Poisson's ratios of 0.35, 0.4, 0.4, and 0.45 were used for surface, base, subbase, and subgrade materials, respectively. A total of 15 thicknesses and 10 moduli combinations were used (150 pavement sections x 4 moduli). The surface thicknesses ranged from 2 to 6 in., the base thicknesses from 4 to 8 in., and the subbase thicknesses from 4 to 12 in. The subgrade was assumed to be semi-infinite. A wide range of layer moduli was also used with typical modulus ranges for each layer.

To expand the scope of the study, the deflection values obtained in the previous step (using static analysis) were used to backcalculate the corresponding layer moduli using the dynamic analysis with subgrade thicknesses of 30 and 60 ft. An iterative scheme was used based on the fact that surface deflections remote from the loaded area are primarily governed by the stiffness of the deeper layers (6,14). In this procedure, the modulus values used in the static solution were assumed as initial moduli for the dynamic solution. The DYNAMIC program is used to calculate deflections at various geophone locations. The calculated deflections are compared with measured deflections. If the deflections do not agree, the moduli are changed through an iterative procedure until a set of modulus values is determined that produces deflections from the DYNAMIC program that match the deflections obtained from the Chevron program. A match is considered adequate when the error in deflection at each geophone location does not exceed 3 percent.

In the DYNAMIC program typical mass densities of 145, 140, 140, and 125 lb/ft^3 were used for surface, base, subbase, and subgrade materials, respectively. Also, a typical material damping ratio of 5 percent was used (15). Meanwhile, Poisson's ratios that were used in the static analysis were also used in the DYNAMIC program. It should be emphasized that minor errors in estimating these parameters do not significantly change the results.

Following the preceding procedure, three sets of layer moduli are available (1,800 moduli). The first set of moduli is associated with the static prediction, and the other two sets of moduli are associated with the dynamic analysis with 30- and 60-ft subgrades. All three sets of moduli have the same deflections but are computed either with different procedures or with different subgrade thicknesses.

The goals were to minimize the number of relationships and maximize the range of applications while maintaining simplicity of use. Therefore, several considerations had to be kept in mind during the development of the typical curves. Because the materials are assumed to be linear, doubling the layer modulus values results in reducing the surface deflections by a factor of 1/2, and so forth. Therefore, normalized curves are developed by dividing the five computed deflections by the computed deflection at Geophone Number 1. This results in five deflection ratios (δ/δ_1) with a unit value at the first geophone. In this case the deflection curves represent certain deflection shapes rather than actual deflection measurements. The normalized curves are shown in Figures 6-13 for various layer thickness combinations. For each thickness combination, 10 normalized curves are shown (A to J) representing 10 moduli ratios.

Three sets of tables have also been prepared to be used with the curves. Table 1 gives the static constants and Tables 2 and 3 present the dynamic factors for 30- and 60-ft subgrades for all thickness and curve combinations. The static constant is defined as the layer modulus based on static analysis times deflection of Geophone Number 1 during the original development of the curves times 31.25 times 2. The factor 31.25 is the peak-to-peak load intensity applied by the Dynaflect on each loading wheel, whereas the factor 2 is used to account for the two wheels. On the other hand, the dynamic factor is defined as the modulus obtained by using dynamic analysis divided by the modulus obtained using the static analysis.

USE OF TYPICAL CURVES AND TABLES

To use the typical curves, the user is expected to know the layer thicknesses from pavement records and the peak-to-peak deflection readings of the five

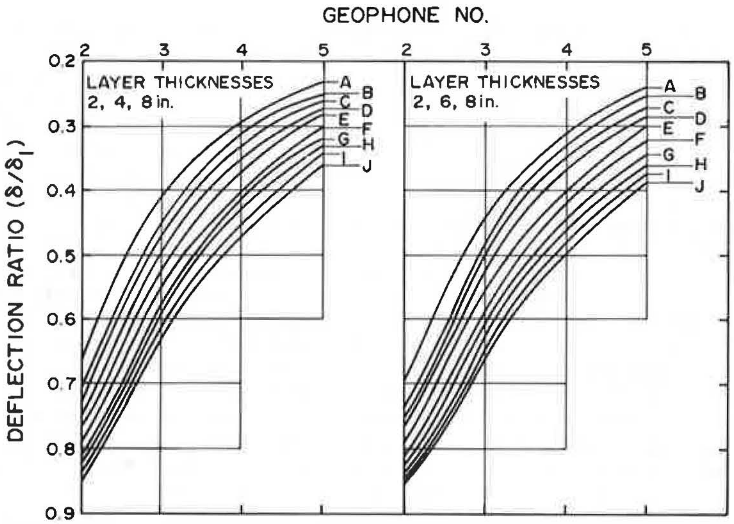

FIGURE 6 Typical normalized deflection curves for layer thicknesses 2, 4, and 8 in. and 2, 6, and 8 in.

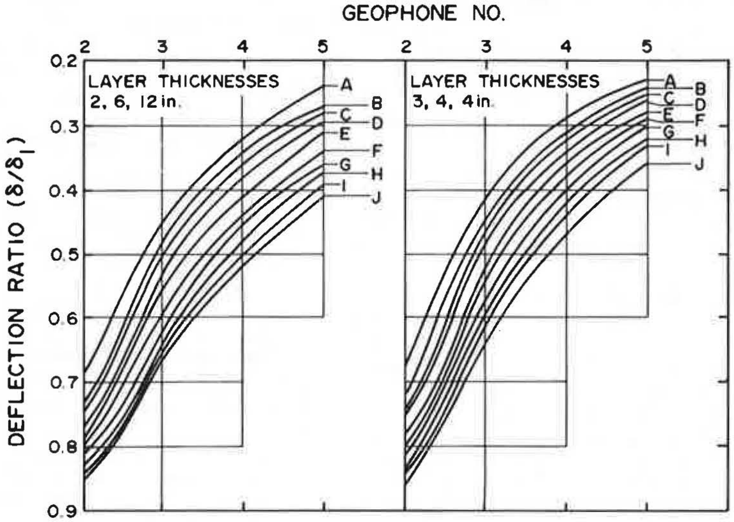

FIGURE 7 Typical normalized deflection curves for layer thicknesses 2, 6, and 12 in. and 3, 4, and 4 in.

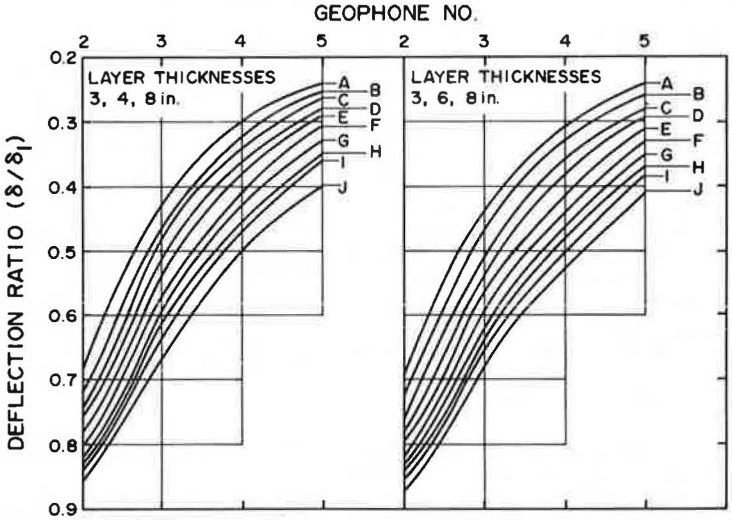

FIGURE 8 Typical normalized deflection curves for layer thicknesses 3, 4, and 8 in. and 3, 6, and 8 in.

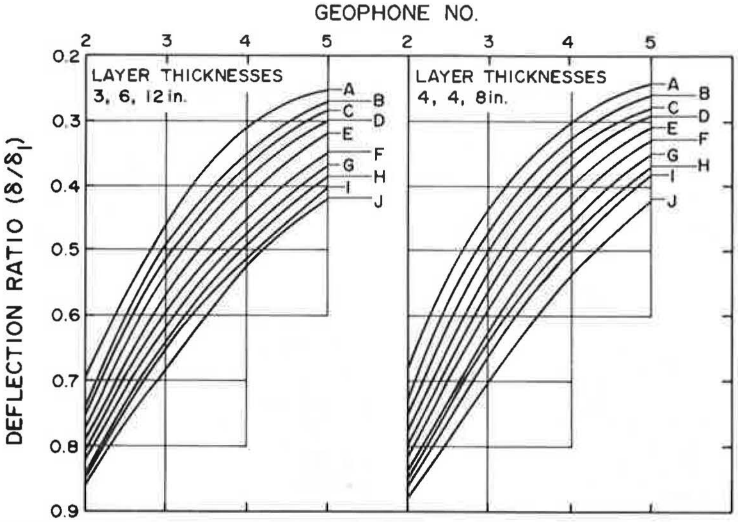

FIGURE 9 Typical normalized deflection curves for layer thicknesses 3, 6, and 12 in. and 4, 4, and 8 in.

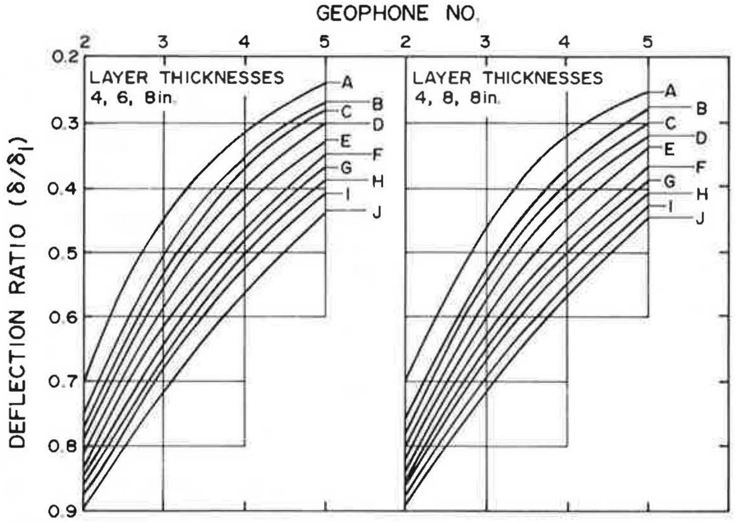

FIGURE 10 Typical normalized deflection curves for layer thicknesses 4, 6, and 8 in. and 4, 8, and 8 in.

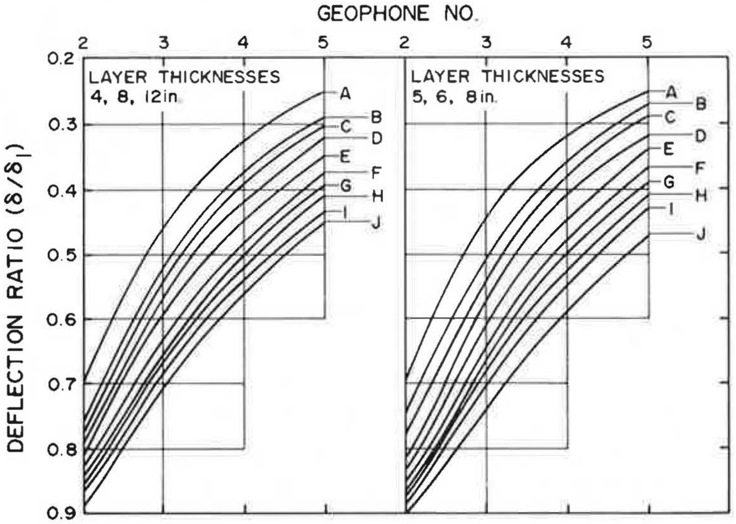

FIGURE 11 Typical normalized deflection curves for layer thicknesses 4, 8, and 12 in. and 5, 6, and 8 in.

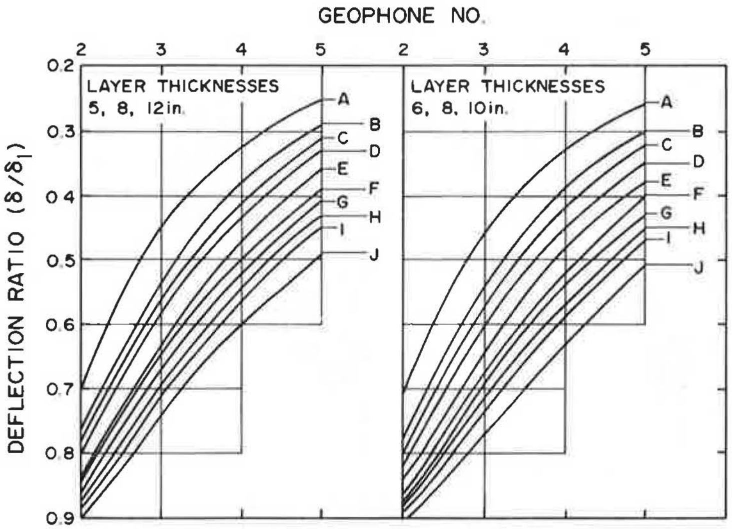

FIGURE 12 Typical normalized deflection curves for layer thicknesses 5, 8, and 12 in. and 6, 8, and 10 in.

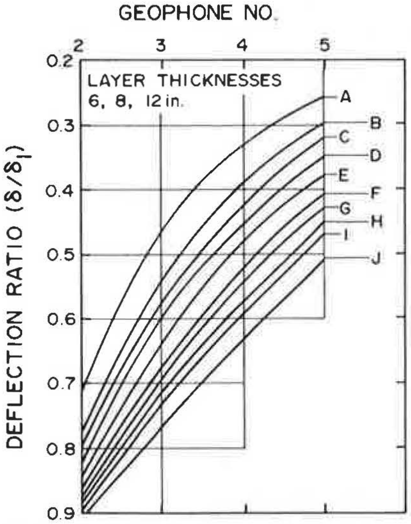

FIGURE 13 Typical normalized deflection curves for layer thicknesses 6, 8, and 12 in.

geophones of the Dynaflect. The deflection ratios are determined, which are the deflection values divided by the deflection at Geophone Number 1. The graph corresponding to the appropriate thickness combination is entered with the deflection ratios and the geophone numbers. The values are plotted and the closest typical curve (A-J) is then determined.

To obtain the layer moduli based on the static solution, the following equation is used:

$$E_{i(\mathrm{static})} = [(\mathrm{static\ constant})_i]/\delta_1 \tag{2}$$

where

$E_{i(\mathrm{static})}$ = modulus of layer i based on static analysis (psi);
i = 1, 2, 3, and 4, representing the surface, base, subbase, and subgrade, respectively;
$(\mathrm{static\ constant})_i$ = value given in Table 1 for Layer i (lb/in.); and
δ_1 = measured peak-to-peak deflection at Geophone Number 1 (in.).

It should be noted that interpolation is allowed in using these curves, but should be used with caution because the curves are not always parallel.

If the layer moduli are sought based on dynamic analysis, the user first has to estimate the approximate depth to bedrock from construction or geological records. The dynamic factors of various layers are then obtained from either Table 2 or Table 3, or interpolated between both tables, and used in the following equation:

$$E_{i(\mathrm{dynamic})} = \{[(\mathrm{static\ constant})_i]/\delta_1\}(\mathrm{dynamic\ factor})_i \tag{3}$$

where

$E_{i(\mathrm{dynamic})}$ = modulus of Layer i based on dynamic analysis (psi), and
$(\mathrm{dynamic\ factor})_i$ = value given in Table 2 or Table 3, or interpolated between both tables for Layer i.

The typical modulus for asphalt concrete is approximately between 100,000 and 700,000 psi, depending on the temperature, and the granular base and subbase moduli should range between 20,000 and 100,000 psi. Typical values of subgrade moduli vary from 3,000-5,000 psi for cohesive clay soils to 20,000-30,000 psi for fine-grained sandy soils. These typical ranges of moduli were used in the development of the curves and tables in this study. Thus, it is not expected that moduli outside of these ranges be obtained based on dynamic analysis if the curves and tables are used.

TYPICAL EXAMPLE

A Dynaflect test was performed on a four-layer flexible pavement with surface, base, and subgrade thicknesses of 4, 4, and 8 in., respectively. Geological records indicate that the bedrock is deep. The Dynaflect peak-to-peak surface deflections are 0.002806, 0.002250, 0.001571, 0.001125, and 0.000860 in. at Geophones 1, 2, 3, 4, and 5, respectively. Using the typical curves and tables developed in this study, it is required that the modulus values of various pavement layers be estimated as well as that of the subgrade based on static and dynamic analyses.

TABLE 1 Static Constants

Thicknesses (in.)	Layer	Curve A	B	C	D	E	F	G	H	I	J
2, 4, 8	1	21.9	12.7	19.4	108	3,285	4,356	3,903	7,207	7,779	1,934
	2	11	10.6	46.3	27.3	109	149	221	111	211	835
	3	40	34	47.3	58.5	55.9	58.9	60.7	75.9	68.4	59.5
	4	22.6	22.1	21.9	21.4	19.9	18.7	17.9	17.1	16.6	16
2, 6, 8	1	21.9	39	20.6	6,427	2,871	3,767	674	4,761	2,507	4,319
	2	22.4	42.1	91.4	64.3	43.1	117	201	178	448	699
	3	41.3	50.5	50.9	73.9	69.6	50.9	64.8	36.3	27.7	16.4
	4	23	21.7	20.9	19.6	18.4	17.4	16.8	16.2	15.9	15.6
2, 6, 12	1	20.8	15.5	499	1,738	2,550	320	3,900	4,344	7,790	2,840
	2	28.6	64.2	298	72.3	119	129	108	118	128	693
	3	36.6	48.2	71.3	40.5	47.9	53.7	40.8	43.3	37.6	27.8
	4	22.6	21.3	20.5	18.7	18	16.8	16.2	15.4	14.9	14.3
3, 4, 4	1	24	13.3	62.8	2,318	3,518	4,780	5,881	424	5,711	9,289
	2	19.1	11.1	31.4	29	52.8	39.8	44.1	47.2	50.2	54.9
	3	86.3	31.5	168	193	81.7	109	92.9	219	172	104
	4	24.6	22.3	22.7	21.7	20.7	19.6	18.9	17.9	17.4	16.3
3, 4, 8	1	453	818	1,144	2,045	3,058	2,828	2,032	1,150	1,945	13,688
	2	34.2	46.2	47.1	34.1	45.9	99.8	200	446	476	593
	3	81.7	29.1	56.4	70.8	61.8	58.3	56.2	54.9	53.1	18.3
	4	23.3	20.6	21.5	20.2	19.2	18	17.2	16.5	15.9	17
3, 6, 8	1	432	765	1,029	1,819	1,965	1,370	4,239	1,615	1,913	3,546
	2	43.6	61.5	73	72.8	105	154	88.9	561	556	257
	3	43.6	38.3	42	45.5	41.8	41.6	63.4	18.7	21.4	26.1
	4	22.7	21.9	20.3	19.1	18	17	16.4	16	15.3	14.6
3, 6, 12	1	377	696	792	179	587	1,150	307	4,421	7,200	5,959
	2	32.9	69.0	40.8	98	109	103	98.5	104	113	172
	3	59.8	35.8	43.3	42.9	39.8	40.7	33.5	31.9	26.4	28.8
	4	19.5	20.6	19.5	18.6	17.4	16.4	15.8	15.1	14.6	13.8
4, 4, 8	1	446	784	52.9	1,358	1,766	1,618	1,039	292	444	3,045
	2	17.6	19.6	26.5	23.8	42.1	48.7	273	584	577	491
	3	89.8	80.4	73.9	81	64.1	35.8	47.6	90	73	22.6
	4	23.3	21.7	21	19.4	18.2	17.2	16.4	15.7	15.2	14.3
4, 6, 8	1	426	715	92.5	1,012	1,011	1,010	1,688	3,524	3,178	9,805
	2	29.5	44.2	53.8	65.5	104	153	154	29.5	224	151
	3	57.3	48.5	53.9	44.7	39.5	35.4	26.3	122	13.3	13.1
	4	22.7	20.6	19.8	18.5	17.4	16.3	15.7	14	14.7	13.5
4, 8, 8	1	326	652	43.3	209	618	1,218	1,720	2,025	4,238	1,729
	2	37.8	60.7	43.7	99	112	116	132	156	24.2	282
	3	45.2	34.8	59.4	52.3	28.7	20.6	15.2	12.2	159	11.4
	4	22.2	19.7	18.9	16.7	16.5	15.8	15.4	14.8	12.2	13.3
4, 8, 12	1	174	30.7	104	321	1,915	1,179	2,109	190	733	387
	2	41.8	64.5	77.9	82.9	80.2	100	104	380	379	84.8
	3	35.8	37.6	35.1	32.6	37.9	26.4	20.9	37.1	16.9	30.7
	4	22	19.4	18.4	17.3	15.5	15.4	14.8	14	13.6	12.5
5, 6, 8	1	320	186	913	735	736	612	1,278	4,519	1,376	1,124
	2	28.1	18.3	22.8	65.7	108	174	169	452	304	525
	3	50.4	147	126	39.9	34	31	20.6	11.3	13.7	11.3
	4	22.4	21.3	17.8	17.8	16.6	15.5	15	11.6	14	13
5, 8, 12	1	374	33.3	759	238	995	336	658	689	1,294	356
	2	58.7	66.3	68.7	85.6	130	127	134	174	176	356
	3	22.4	35.7	27	31.6	15.3	29.4	23.1	21.6	15.6	28.2
	4	22.7	19	18.4	16.7	16.7	14.8	14.2	13.6	13.1	11.8
6, 8, 10	1	111	132	79.6	1,232	192	191	1,258	584	253	333
	2	36.1	63.8	88.9	44.7	205	16.7	18.9	214	326	416
	3	38.3	30.8	32.8	23.2	23	26.6	126	12.7	23.8	24.7
	4	21.6	18.7	17.5	15.9	15.7	14.5	12	13.3	12.4	11.4
6, 8, 12	1	125	47.8	91.9	173	281	215	354	268	240	3,610
	2	35.5	67.9	81.8	94.9	116	162	174	241	266	19.7
	3	39.7	32.4	31.1	30.2	26.3	26.3	21.9	24.7	29.1	35.5
	4	21.3	18.6	17.4	16	14.9	14.3	13.7	12.8	12.2	11.1

The first step is to determine the deflection ratios δ/δ_1 as 0.8, 0.56, 0.4, and 0.31 at Geophones 2, 3, 4, and 5, respectively. By plotting these deflection ratios on the figure corresponding to layer thicknesses of 4, 4, and 8 in. (Figure 9), it can be observed that the data fit Curve E. The static constants are obtained from Table 1 as 1,766, 42.1, 64.1, and 18.2 for the surface, base, subbase, and subgrade, respectively. By using Equation 2, the moduli of various materials are calculated as follows:

$E_{1\,(\text{static})}$ = 1,766/0.002806 = 629,400 psi.

$E_{2\,(\text{static})}$ = 42.1/0.002806 = 15,000 psi.

$E_{3\,(\text{static})}$ = 64.1/0.002806 = 22,800 psi.

$E_{4\,(\text{static})}$ = 18.2/0.002806 = 6,500 psi.

To obtain the layer moduli based on the dynamic analysis, the dynamic factors are determined. These factors are obtained from Table 3 as 0.402, 2.7, 0.666, and 0.797 for the surface, base, subbase, and subgrade, respectively. By using Equation 3, the moduli are as follows:

$E_{1\,(\text{dynamic})}$ = 629,400 x 0.402 = 253,000 psi.

$E_{2\,(\text{dynamic})}$ = 15,000 x 2.7 = 40,500 psi.

$E_{3\,(\text{dynamic})}$ = 22,800 x 0.666 - 15,200 psi.

$E_{4\,(\text{dynamic})}$ = 6,500 x 0.797 = 5,200 psi.

SIGNIFICANCE OF THE DYNAMIC ANALYSIS

The inertia of the pavement system is reflected in the dynamic factors given in Tables 2 and 3. Ob-

TABLE 2 Dynamic Factors for 30-ft Subgrade

Thicknesses (in.)	Layer	Curve									
		A	B	C	D	E	F	G	H	I	J
2, 4, 8	1	4	13.3	1.32	5	0.25	0.25	0.338	0.25	0.286	2.07
	2	4	8	3.72	3.97	1.21	0.976	0.715	1.51	0.844	0.24
	3	0.823	1.12	0.723	0.771	0.881	0.987	1.09	0.949	1.14	1.35
	4	0.969	0.98	0.901	0.842	0.824	0.775	0.737	0.701	0.669	0.627
2, 6, 8	1	4	4	1.3	0.075	0.25	0.25	1.63	0.322	0.75	0.75
	2	1.96	1.85	0.972	1.5	2.67	1.07	0.656	0.802	0.335	0.232
	3	0.796	0.694	0.699	0.544	0.619	0.987	0.848	1.69	2.38	3.94
	4	0.952	0.897	0.85	0.819	0.781	0.722	0.653	0.629	0.592	0.52
2, 6, 12	1	4	9.36	0.5	0.25	0.25	2.55	0.25	0.296	2	0.977
	2	1.46	1.13	0.28	1.2	0.859	0.844	1.09	1.02	0.974	2
	3	0.851	0.753	0.466	0.895	0.798	0.81	1.2	1.19	1.45	2
	4	0.919	0.85	0.813	0.773	0.709	0.646	0.604	0.556	0.523	0.484
3, 4, 4	1	4	13.3	5	0.25	0.25	0.25	0.25	0.477	0.44	0.473
	2	2.51	8	3.33	4	2.67	4	4	4	4	4
	3	0.416	1.27	0.25	0.25	0.646	0.584	0.792	0.37	0.512	0.844
	4	0.975	0.993	0.924	0.891	0.85	0.812	0.779	0.753	0.722	0.672
3, 4, 8	1	0.2	0.2	0.25	0.25	0.25	0.355	0.594	1.42	1.03	0.267
	2	1.33	1.77	2.03	3	2.67	1.34	0.725	0.342	0.337	0.308
	3	0.695	0.706	0.7	0.602	0.743	0.92	1.07	1.19	1.32	4
	4	0.958	0.917	0.888	0.842	0.796	0.745	0.702	0.661	0.629	0.538
3, 6, 8	1	0.2	0.2	0.25	0.25	0.34	0.636	0.25	0.868	0.894	0.843
	2	0.991	1.24	1.17	1.25	1.02	0.753	1.43	0.233	0.246	0.582
	3	0.744	0.899	0.817	0.832	0.96	1.12	0.835	2.99	2.8	2.29
	4	0.951	0.875	0.846	0.794	0.742	0.685	0.648	0.585	0.558	0.513
3, 6, 12	1	0.2	0.2	0.3	2.3	1.02	0.662	2.91	0.269	0.2	0.423
	2	1.14	1.01	1.94	0.84	0.877	0.984	1.09	1.07	1.02	0.731
	3	0.473	0.875	0.732	0.8	0.902	0.998	1.33	1.5	1.91	1.75
	4	0.966	0.845	0.812	0.739	0.688	0.618	0.567	0.524	0.494	0.455
4, 4, 8	1	0.2	0.2	5	0.351	0.397	0.564	1.05	5	4	0.993
	2	2.54	4	3.33	4	2.67	0.25	0.48	0.233	0.246	0.308
	3	0.373	0.439	0.477	0.49	0.657	1.36	1.14	0.649	0.851	2.68
	4	0.957	0.904	0.841	0.818	0.77	0.71	0.665	0.62	0.586	0.528
4, 6, 8	1	0.2	0.2	2.59	0.42	0.61	0.79	0.561	0.359	0.482	0.267
	2	1.44	1.62	1.49	1.3	0.952	0.696	0.738	4	0.548	0.868
	3	0.557	0.664	0.593	0.792	0.81	1.2	1.8	0.414	4.04	4
	4	0.936	0.869	0.806	0.767	0.711	0.653	0.604	0.6	0.522	0.484
4, 8, 8	1	0.249	0.2	5	1.82	0.885	0.578	0.483	0.547	0.296	1.32
	2	1.07	1.07	1.65	0.77	0.784	0.808	0.754	0.663	4	0.405
	3	0.673	0.84	0.486	0.804	1.14	1.82	2.73	3.63	0.267	4
	4	0.914	0.828	0.763	0.723	0.661	0.594	0.541	0.5	0.496	0.43
4, 8, 12	1	0.444	4	1.97	1.1	0.25	0.534	0.348	5	1.59	5
	2	0.927	0.95	0.878	0.847	0.956	0.837	0.846	0.233	0.246	1.14
	3	0.81	0.733	0.779	0.897	0.758	1.27	1.76	1.02	2.41	1.26
	4	0.88	0.791	0.742	0.675	0.62	0.544	0.495	0.452	0.43	0.387
5, 6, 8	1	0.26	0.787	0.25	0.535	0.766	1.18	0.668	0.25	1	2.01
	2	1.48	4	3.33	1.2	0.833	0.553	0.605	0.233	0.358	0.215
	3	0.618	0.225	0.243	0.821	0.993	1.25	2.07	4	3.48	4
	4	0.928	0.861	0.855	0.738	0.679	0.622	0.568	0.65	0.487	0.436
5, 8, 12	1	0.2	3.52	0.25	1.38	0.452	1.72	1.02	1.28	0.819	5
	2	0.638	0.884	0.922	0.767	0.554	0.607	0.6	0.475	0.482	0.25
	3	1.26	0.74	0.938	0.866	1.76	1.05	1.46	1.64	2.38	1.26
	4	0.826	0.772	0.687	0.657	0.539	0.521	0.475	0.435	0.404	0.376
6, 8, 10	1	0.68	0.866	2.36	0.25	2.24	2.9	0.5	1.45	4	5
	2	1.04	0.899	0.703	1.38	0.335	0.444	4	0.37	0.249	0.2
	3	0.735	0.836	0.763	1.11	2.24	1.12	0.25	2.67	1.49	1.35
	4	0.87	0.764	0.716	0.644	0.548	0.511	0.524	0.423	0.408	0.367
6, 8, 12	1	0.59	2.34	1.99	1.76	1.52	2.47	1.74	3	4	0.437
	2	1.04	0.822	0.744	0.643	0.586	0.438	0.425	0.311	0.29	4
	3	0.7	0.775	0.783	0.843	0.969	1.08	1.41	1.3	1.15	0.889
	4	0.868	0.753	0.699	0.637	0.57	0.496	0.451	0.42	0.393	0.356

viously, when the dynamic factor is close to 1 the inertial effect can be neglected, otherwise it is significant. It can be easily observed from the tables that the dynamic factors vary widely between 0.2 and 13.3 for all pavement sections, which indicates that the static analysis either underestimates or overestimates the layer moduli. In fact, the moduli of some layers are underestimated and the moduli for other layers are overestimated in the same pavement section with no consistent trend because of the use of static analysis. For example, by using static analysis, a modulus for an upper layer that is lower than that for a lower layer may be obtained. This discrepancy between static results and actual material properties is mainly due to the inconsistency between the type of load in the field and the method of analysis. Also, the inconsistency in the dynamic factor values indicates that Tables 2 and 3 cannot easily be reduced to simpler or smaller tables because the dynamic response of pavement is a complex function of material properties, layer thicknesses, loading mode, loading frequency, or some combination of these.

The results also indicate that the effect of changing the depth to bedrock on the layer moduli is not as large as the effect of changing the method of analysis (static versus dynamic). This is explained, in many cases, by the similarity of factors in Tables 2 and 3.

LIMITATIONS

Although the curves and tables developed in this paper provide a simple and convenient method for evaluating the layer stiffnesses of existing pave-

TABLE 3 Dynamic Factors for 60-ft Subgrade

Thicknesses (in.)	Layer	Curve									
		A	B	C	D	E	F	G	H	I	J
2, 4, 8	1	4.37	13.6	1.38	5.09	0.255	0.255	0.341	0.254	0.29	2.09
	2	4.34	8.11	3.83	4.02	1.23	0.992	0.721	1.53	0.854	0.243
	3	0.852	1.13	0.745	0.781	0.888	1	1.11	0.963	1.16	1.38
	4	0.996	1	0.946	0.872	0.86	0.823	0.774	0.736	0.69	0.66
2, 6, 8	1	4.12	4.06	1.33	0.076	0.255	0.253	1.69	0.327	0.763	0.775
	2	2.02	1.88	1	1.53	2.71	1.08	0.686	0.82	0.342	0.244
	3	0.828	0.706	0.728	0.552	0.629	1.01	0.895	1.73	2.4	4.17
	4	1	0.926	0.894	0.858	0.819	0.749	0.716	0.658	0.631	0.592
2, 6, 12	1	4.12	9.38	0.496	0.253	0.252	2.58	0.251	0.298	0.204	0.98
	2	1.5	1.14	0.273	1.22	0.871	0.843	1.1	1.03	0.983	0.201
	3	0.885	0.69	0.46	0.912	0.816	0.833	1.21	1.21	1.47	2.04
	4	0.965	0.9	0.863	0.813	0.742	0.69	0.639	0.59	0.563	0.515
3, 4, 4	1	4.04	13.7	5.15	0.254	0.254	0.253	0.253	0.481	0.445	0.474
	2	2.49	8.13	3.43	4.05	2.7	4.06	4.05	4.05	4.05	4.06
	3	0.413	1.3	0.258	0.252	0.656	0.595	0.802	0.375	0.521	0.859
	4	1.02	1.03	0.97	0.927	0.877	0.835	0.804	0.779	0.744	0.69
3, 4, 8	1	0.206	0.201	0.253	0.249	0.254	0.359	0.598	1.42	1.04	0.267
	2	1.38	1.77	2.05	2.99	2.71	1.36	0.737	0.341	0.342	0.308
	3	0.716	0.705	0.684	0.598	0.753	0.945	1.1	1.19	1.35	4.06
	4	1.01	0.971	0.922	0.878	0.835	0.771	0.74	0.668	0.653	0.57
3, 6, 8	1	0.164	0.199	0.253	0.253	0.346	0.643	0.257	0.88	0.897	0.844
	2	0.821	1.25	1.19	1.26	1.03	0.76	1.49	0.239	0.25	0.594
	3	0.83	0.909	0.819	0.845	0.975	1.15	0.888	3.06	2.86	2.35
	4	1	0.885	0.893	0.826	0.773	0.718	0.702	0.619	0.596	0.534
3, 6, 12	1	0.204	0.203	0.298	2.31	1.01	0.671	2.92	0.272	0.199	0.423
	2	1.15	0.992	1.91	0.854	0.871	1.01	1.11	1.08	1.01	0.733
	3	0.466	0.825	0.716	0.815	0.895	1.01	1.37	1.53	1.9	1.78
	4	1.01	0.913	0.866	0.777	0.714	0.657	0.604	0.551	0.494	0.471
4, 4, 8	1	0.206	0.201	5.14	0.356	0.402	0.568	1.06	5.02	4.01	1.01
	2	2.62	4.02	3.48	4.05	2.7	0.255	0.485	0.234	0.25	0.308
	3	0.384	0.441	0.499	0.498	0.666	1.38	1.58	0.654	0.86	2.73
	4	1.01	0.934	0.884	0.853	0.797	0.751	0.689	0.652	0.623	0.556
4, 6, 8	1	0.239	0.203	2.65	0.424	0.616	0.795	0.566	0.367	0.49	0.264
	2	1.55	1.64	1.57	1.3	0.968	0.705	0.751	4.02	0.557	0.864
	3	0.517	0.67	0.612	0.811	0.961	1.23	1.83	0.421	4.13	4.08
	4	0.991	0.915	0.85	0.812	0.748	0.695	0.65	0.642	0.542	0.525
4, 8, 8	1	0.257	0.202	5.15	1.85	0.894	0.582	0.484	0.551	0.295	1.34
	2	1.1	1.1	1.7	0.78	0.797	0.822	0.768	0.678	4.19	0.408
	3	0.684	0.857	0.504	0.824	1.17	1.87	2.79	3.72	0.287	3.97
	4	0.986	0.885	0.81	0.753	0.693	0.628	0.577	0.532	0.547	0.47
4, 8, 12	1	0.447	4.12	1.98	1.08	0.254	0.538	0.35	5.11	1.61	5.07
	2	0.935	0.979	0.888	0.837	0.988	0.846	0.864	0.242	0.251	1.15
	3	0.818	0.755	0.791	0.896	0.81	1.29	1.77	1.11	2.41	1.38
	4	0.939	0.831	0.791	0.735	0.683	0.585	0.539	0.524	0.469	0.451
5, 6, 8	1	0.265	0.791	0.254	0.538	0.763	1.19	0.664	0.247	0.98	1.95
	2	1.5	4.06	3.4	1.21	0.831	0.562	0.618	0.235	0.363	0.198
	3	1.62	0.226	0.248	0.833	0.992	1.27	2.14	4.11	3.59	3.55
	4	0.985	0.906	0.898	0.778	0.682	0.674	0.61	0.701	0.505	0.486
5, 8, 12	1	0.202	3.55	0.251	1.37	0.452	1.74	1.02	1.3	0.811	5
	2	0.642	0.894	0.56	0.778	0.563	0.607	0.607	0.477	0.491	0.249
	3	1.26	0.758	0.953	0.889	1.79	1.1	1.47	1.67	2.38	1.3
	4	0.86	0.809	0.742	0.709	0.567	0.568	0.519	0.426	0.441	0.386
6, 8, 10	1	0.687	0.871	2.36	0.258	2.31	2.94	1.55	1.45	3.99	0.49
	2	1.05	0.909	0.714	1.42	0.345	0.448	4.12	0.364	0.253	0.199
	3	0.744	0.845	0.793	1.14	2.33	1.14	0.26	0.272	1.52	1.38
	4	0.918	0.83	0.771	0.676	0.575	0.541	0.55	0.481	0.438	0.394
6, 8, 12	1	0.592	2.29	1.96	1.75	1.51	2.43	1.77	2.99	3.84	0.434
	2	1.05	0.807	0.732	0.644	1.69	0.43	0.423	0.31	0.279	3.8
	3	0.711	0.754	0.77	0.865	0.996	1.06	1.41	1.32	1.14	0.911
	4	0.919	0.794	0.736	0.689	0.613	0.495	0.495	0.446	0.391	0.403

ments, they have some limitations. In a small number of cases, field deflections may cross one or more of the typical curves. In such cases interpretation of results may not provide accurate estimates. Another source of error might develop because of the use of a backcalculation procedure in developing the tables. Because backcalculations in many cases do not result in unique solutions, the estimated moduli may not be accurate. However, this error is not expected to significantly alter the prediction of the load-carrying capacity of the pavement system or the required overlay thickness. Field verifications or other independent validation procedures are still needed to support the results obtained in this study.

Also, the typical curves and tables are intended to be used with the Dynaflect data only because the Dynaflect has some unique characteristics that are different from those of other nondestructive devices, such as load magnitude, frequency of loading, location of loading wheels, and location of geophones. Moreover, the layer thicknesses used in this study may not completely cover all thicknesses encountered in the field. However, the limitations associated with the use of the curves and tables are believed to be insignificant when their usefulness and simplicity are taken into consideration.

It should be noted that the Dynaflect has some limitations, such as the small load magnitude, which might not accurately detect the material properties at deep layers, and the fixed loading frequency, which might result in a resonant pavement response.

SUMMARY

Because there is no direct solution for providing the pavement layer stiffnesses from deflection measurements, typical curves and tables are developed in this study to aid the highway engineer in this respect. These curves and tables provide the layer moduli of typical highway pavements from the peak-to-peak deflection readings of the Dynaflect. The development of the curves and tables is based on the principles of mechanics using both static and dynamic analyses. Pavement sections are used with four typical layers: surface, base, subbase, and subgrade. Materials are assumed to be homogeneous and isotropic, with linear elastic behavior in the static solution and linear viscoelastic behavior in the dynamic solution. Typical Poisson's ratios, material damping ratios, and mass densities are assumed. If the layer thicknesses and the approximate depth to bedrock are known, the layer moduli can be predicted with a reasonable degree of accuracy. The curves are simple to use without the need for previous empirical relations or computer analysis.

The inertial effect of the pavement structure in most cases proved to be influential in evaluating the layer moduli. The dependence on the static solution in the interpretation of the dynamic Dynaflect deflections can either underestimate or overestimate the moduli, which may have significant effects on the predicted load-carrying capacity, the required overlay thickness, or both.

ACKNOWLEDGMENT

The authors wish to thank the Center for Advanced Research in Transportation and the Department of Civil Engineering at Arizona State University for making their facilities available to them.

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