

# Theoretical Response of Multilayer Pavement Systems to Dynamic Nondestructive Testing

TREVOR G. DAVIES and MICHAEL S. MAMLOUK

## ABSTRACT

Nondestructive testing of highway and airport pavements has become increasingly popular. Although dynamic loading devices have become the method of choice because their field operation is relatively simple, fast, and economical, analysis of the test data remains problematic. Using a rigorous elastodynamic formulation, it is demonstrated in this paper that the dynamic phenomena of resonance and inertial damping within the subgrade may result in significant differences in pavement response to static and dynamic loading. Because static analyses are currently used to analyze the latter, significant errors may arise in back-calculating layer stiffnesses, particularly because the iterative schemes used in such analyses are ill-conditioned. Examination of the data obtained from a study of the response of four-layer flexible pavements to excitation by the Road Rater device for a wide range of frequencies suggests that no simple correlation between dynamic and static deflections can be developed. Some improvement in current practice may be effected by carrying out tests over the entire operating range of frequencies to ensure that the measured deflections are not corrupted by spurious subgrade resonances.

Nondestructive testing has been extensively used in the last few decades for evaluation of the load-deformation response of highway and airfield pavement systems. The results of such surveys have significant impact on the operation and maintenance of these facilities and, therefore, accurate interpretation of the test data is important.

Nondestructive testing can be divided into two main types: seismic techniques (associated with time measurements) and surface loading tests (associated with deflection measurements). Extraction of layer stiffnesses from these data is the crux of the problem, which has not yet been fully resolved.

The seismic techniques normally employed in highway engineering are based on measurement of the velocities of the Rayleigh waves (surface waves) of the pavement system (1,2). Such techniques have not gained wide acceptance, partly as a consequence of the relative sophistication required in field operation and in interpretation of the test data. Surface loading tests, on the other hand, have been extensively used by many highway agencies because of their simplicity and their ability to model real traffic load intensities and durations. Thus the stiffnesses computed from surface deflection measurements are more nearly representative of field conditions.

Surface deflection measurement devices can be categorized as static (e.g., Benkelman Beam, California Traveling Deflectometer) and dynamic [e.g., Dynaflect, Road Rater, various vibratory devices (3), falling weight deflectometer]. The Dynaflect, the Road Rater, and the vibratory devices impart steady-state dynamic (harmonic) loading to loading plates, whereas the falling weight deflectometer imparts an impulsive load developed by a weight falling on a spring-loaded single plate. Most of the vibratory devices are capable of generating a wide range of loading frequencies and for that reason are preferred to the single frequency Dynaflect. Although the falling weight deflectometer simulates

traffic loading somewhat better than do harmonic loading devices, a high degree of correlation between the test data obtained from the Road Rater and the falling weight deflectometer has been reported (4).

Analyses of the data obtained from dynamic loading devices have hitherto been based on either empirical approaches or elastostatic and viscoelastostatic models (5-9). Obviously, empirical correlations are restricted to conditions similar to those in which such correlations were originally developed, and, in the static analyses, the inertia of the pavement is neglected. In other words, it is assumed that the dynamic response of pavement structures is no different from the static response.

Experimental work performed by others emphasizes the difference between static and dynamic responses of pavement systems. For example, Hoffman and Thompson (4) operated a circular plate Road Rater at peak-to-peak loads of 2, 4, 6, and 8 kips and driving frequencies of between 6 and 30 Hz at 2-Hz intervals for each load. The results of those tests are shown in Figure 1 for three pavement sections with various layer thicknesses and material properties. The experimental results show that resonant frequencies (natural vibration frequencies) of 10, 18, and 16 Hz existed for the three pavement sections, respectively. These resonant frequencies were almost independent of load intensity and were within the normal range of operating frequencies. The resonant frequencies were different from one pavement section to another depending on layer thicknesses and material properties. The resonant frequencies of the pavement systems cannot be explained by any static analysis.

In this paper, an elastodynamic solution is used to show that the static and dynamic responses of pavements may be significantly different even at low frequencies (Figure 2). This rather complex approach is necessary because one-degree of freedom approximations [e.g., Weiss (10)] cannot reproduce all

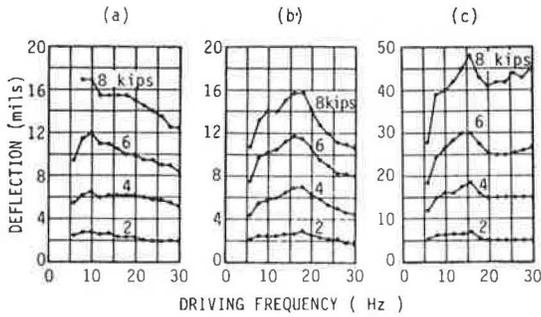


FIGURE 1 Experimental peak-to-peak deflection versus driving frequency of the Road Rater at three pavement sections (a) Sherrard: 4 in. AC, 14 in. crushed stone, (b) Monticello: 3.5 in. AC, 8 in. plant CAM, and (c) Deland: surface treatment, 8 in. granular base B (4).

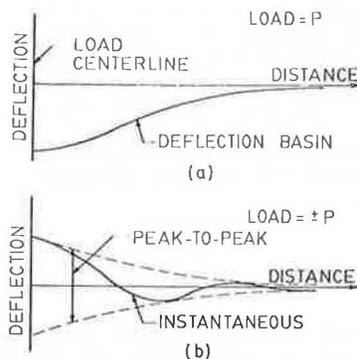


FIGURE 2 Surface deflection profiles for (a) static loading and (b) dynamic loading.

facets of the dynamic behavior of multi-degree of freedom pavement systems.

An analysis of the Road Rater device is presented. Similar results are to be expected for harmonic loading devices such as the Dynaflect and impulsive loading devices such as the falling weight deflectometer.

#### INTERPRETATION OF DEFLECTION DATA

Although empirical rules for assessing the integrity of pavements on the basis of nondestructive test data are commonly employed, in practice there is an increasing trend toward adoption of methods based on theoretical models of pavements. However, the inverse problem of determining material properties from pavement deflections caused by prescribed loads is difficult even if the assumption of linear elastic behavior of isotropic layers is valid. Given limited data, no unique solution can be determined although in practice the range of admissible solutions may be relatively narrow. The problem is compounded because it is necessary to employ iterative schemes [e.g., Kilareski and Anani (7)] to solve the inverse problem. Although the stiffness of the subgrade can often be determined reasonably accurately, the iterative schemes employed in practice are necessarily ill-conditioned and inevitably magnify the data and modeling errors. Thus, for the upper layers, the predicted stiffnesses may be considerably in error.

In principle, nonlinear elastic models of pavement structures (5) would appear to offer some im-

provement over the simpler linear analyses commonly used. Unfortunately, there are grave difficulties in applying such analyses in practice. Among these are the uncertainties in determining the in situ stress state, selection of an appropriate constitutive law, and determination of the material parameters. Subgrade response may depend on whether loading takes place under drained or undrained conditions, which in turn is dependent on soil type and loading rate.

Moreover, potentially grave modeling errors result from neglecting the inertial response of pavements to dynamic excitation. In the following sections, a brief description of an elastodynamic algorithm for harmonic loading of horizontally layered strata is described. The deflections predicted by this model are quite different from those of an equivalent static analysis. Thus the solution of the inverse problem using a static analysis may be subject to significant error.

#### METHOD OF ANALYSIS

The governing equation for steady-state elastodynamics (i.e., harmonic motion) is the well-known Helmholtz equation (11)

$$C_p^2 \text{grad}(\text{div } \underline{u}) - C_s^2 \text{curl}(\text{curl } \underline{u}) + \rho^2 \omega^2 \underline{u} = 0 \quad (1)$$

where  $C_p$  and  $C_s$  are the pressure and shear wave velocities, respectively;  $\underline{u}$  is the displacement vector; and  $\omega$  is the circular frequency of excitation. The displacement vector in Equation 1 can be expressed in the form:

$$\underline{u}(t) = \underline{u}^* e^{i\omega t} \quad (2)$$

in which  $\underline{u}^*$  are the (complex) amplitudes of the displacement vector,  $t$  denotes time, and  $i$  is the unit imaginary number. The wave velocities are related to the stiffness and mass density of the solid by the equations:

$$C_p = \{[E(1 - \mu)] / [(1 + \mu)(1 - 2\mu)\rho]\}^{1/2} \quad (3)$$

$$C_s = \{E / [2(1 + \mu)\rho]\}^{1/2} \quad (4)$$

where  $E$ ,  $\mu$ , and  $\rho$  are the Young's modulus, Poisson's ratio, and mass density, respectively.

Clearly, integration of Equation 1 for any but the simplest boundary conditions is impossible by analytical means. The only closed-form solution available is for a point load excitation in an infinitely extensive homogeneous medium. Solutions for the present (layered) problem must therefore be obtained by numerical means. In this analysis, the usual assumptions of material linearity and isotropy are invoked. Soil and pavement layers are assumed to be unbounded laterally but are underlain by a rigid (reflective) bedrock layer at a finite depth, and full interface bonding (no slip) conditions are assumed at the layer interfaces.

The numerical solution of Kausel and Peek (12), which is used here, involves subdivision of the given layered system into thin artificial sublayers. For each sublayer, a stiffness matrix in the so-called frequency-wave number (transform) domain may be found:

$$\begin{bmatrix} \bar{P}_1 \\ \bar{P}_2 \end{bmatrix} = [K] \begin{bmatrix} \bar{U}_1 \\ \bar{U}_2 \end{bmatrix} \quad (5)$$

in which the superscript bar indicates transformed quantities;  $\bar{P}$  and  $\bar{U}$  are interface forces and displacements; subscripts 1 and 2 denote the upper and lower interfaces, respectively; and  $[K]$  is a matrix whose elements are simple algebraic functions of the mass densities and elastic moduli of the layer and the frequency of excitation. The simple form of  $[K]$  follows from the assumption that the displacements vary linearly (in the direction of layering) between adjacent interfaces. It is important, therefore, that sufficiently thin layers be specified to preserve accuracy. Stiffness matrices for each layer can then be assembled, in the finite element sense, to form a global stiffness matrix. The relative simplicity of this approximate method, in comparison with the "exact" methods that involve numerical evaluation of highly oscillatory infinite integrals (13), renders the layered pavement structure problem tractable.

#### PAVEMENT PROPERTIES

##### Material Damping

Material damping refers to the internal energy dissipation that occurs in real materials subjected to dynamic loading. Granular pavement materials (e.g., gravels) exhibit hysteretic damping behavior manifested by a frequency-invariant damping ratio; typical values for the damping ratio for such soils are approximately 5 percent (14). This value is adopted in the numerical study that follows. It should be noted, however, that by far the major component of energy dissipation in pavements results from radiation (geometric) damping; that is, the dispersion of energy from the source of excitation to the far field. Using the correspondence principle of viscoelasticity, material damping can be easily incorporated in the analysis by replacing Young's modulus in Equations 3 and 4 by its complex counterpart; that is,

$$E^* = E(1 + 2i\beta) \quad (6)$$

where  $\beta$  is the damping ratio.

##### Resilient and Dynamic Moduli

The stress-strain relations of isotropic elastic materials are, in classical formulations, expressed in terms of fundamental material parameters (e.g., Young's modulus and Poisson's ratio). But in highway engineering it has become common to define state-dependent parameters such as the resilient modulus and the dynamic modulus. These parameters are often used to interpret the nonlinear and the time-dependent response of pavement materials. The resilient modulus is obtained by subjecting a specimen to repeated stress reversals and measuring the recoverable strain after a number of load applications, as shown in Figure 3. The resilient modulus, therefore, is the Young's modulus of the material after many load repetitions (i.e., the shake-down modulus of the material), which is normally different from the initial value. On the other hand, the dynamic modulus is obtained by subjecting a finite specimen to harmonic loading; it is simply the ratio of the stress amplitude to the corresponding strain amplitude as shown in Figure 4.

Clearly, the resilient modulus is relevant in analyses of pavement deflections in that field data reflect the current stiffness of pavements. However, the dynamic modulus is irrelevant (except as noted later) to dynamic analyses of pavement deflections notwithstanding the apparently widely held contrary

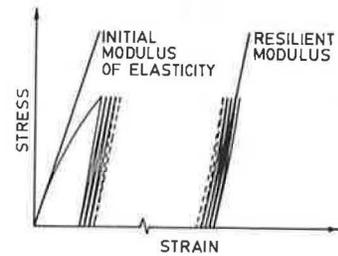


FIGURE 3 Definition of resilient modulus.

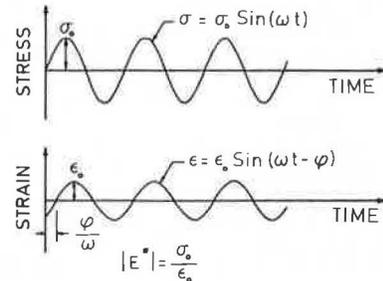


FIGURE 4 Definition of dynamic modulus.

view. Clearly, because the elastodynamic equations of equilibrium cannot be recovered from the corresponding static equations by substituting frequency-dependent moduli, analyses based on such methods must be inconsistent and often yield completely erroneous results. Such analyses cannot, for example, predict a resonant condition.

Laboratory measured values of complex moduli can, however, yield valuable information on the fundamental material parameters (stiffness, internal damping) provided that these tests are properly interpreted (e.g., with due recognition of the inertia of the specimen itself). Such data, combined with a rigorous elastodynamic theory for the pavement structure, offer the greatest promise for real progress in evaluating the response of pavements to moving loads.

#### ANALYSIS AND RESULTS

The theoretical analysis of the twin-plate Road Rater device (Figure 5) involved idealization of the loading platens by two flexible circular plates 3 in. in radius spaced 10.5 in. center-to-center. The geophones were assumed to be located 12 in. apart with the first one located midway between the two platens. Surface deflections were computed at each of the four geophones for a number of representative

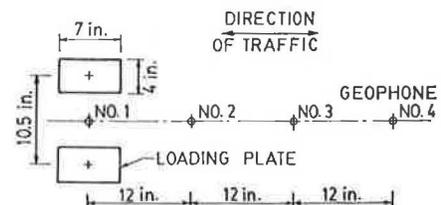


FIGURE 5 Schematic diagram of the Road Rater.

TABLE 1 Properties of Pavement Layers

Layer	Thickness H(in.)			Young's Modulus E(ksi)			Poisson's Ratio $\mu$	Mass Density (lbm/ft <sup>3</sup> )
	Thin	Medium	Thick	Soft	Medium	Stiff		
Surface	1	2	4	100	500	2,000	0.35	150
Base	3	6	12	50	100	200	0.40	145
Subbase	6	12	24	10	20	40	0.40	135
Subgrade	150	150	150	4	8	16	0.45	120

pavement structures (Table 1) for frequencies of excitation of 0 to 50 Hz, which broadly encompass the capability of the Road Rater.

Figure 6 shows the displacement at the first geophone as a function of layer thickness and stiffness under static and harmonic (25 Hz) loading conditions of unit stress intensity. For both static and dynamic loading conditions, deformations are greatest for the thin, soft pavements. Moreover, in all cases the static displacements are greater than the dynamic displacements. For the thick, soft pavement, the static displacements are 50 percent greater than the dynamic displacements.

Typical data illustrating the influence of increasing frequency on the deflections measured at the geophones are shown in Figure 7. These data are

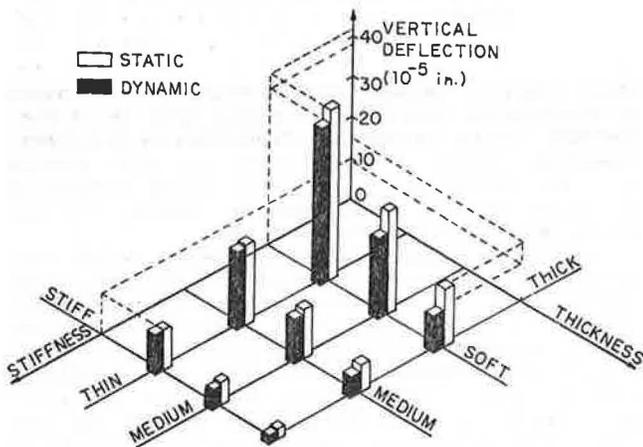


FIGURE 6 Surface deflections at geophone 1 under unit static and 25 Hz dynamic loading conditions.

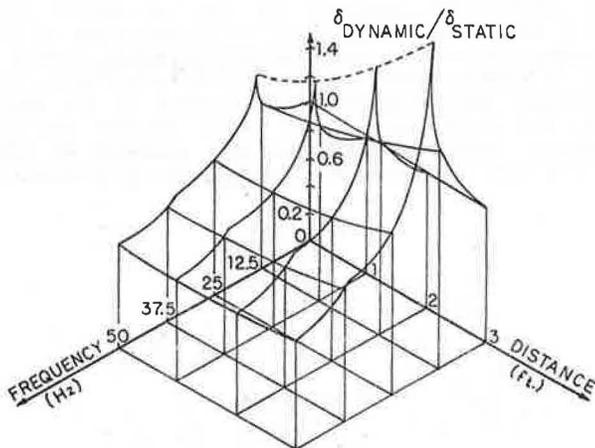


FIGURE 7 Dynamic-to-static surface deflection ratios for medium thickness, stiff pavement.

normalized with respect to the static deflections. For each geophone, the dynamic deflections initially increase sharply with increasing frequency but thereafter decay. A medium thickness, stiff pavement was analyzed to obtain these data although similar results were obtained for pavements with the same geometry but consisting of medium stiffness and soft materials, respectively.

The initial increase in deflection at low frequencies is due to excitation of resonance in the subgrade (a phenomenon that is explored in more detail subsequently), and the relatively low deflections at higher frequencies are a manifestation of inertial effects. Neither of these phenomena can be reproduced by static analyses of this problem. Although the trend of the results is similar for pavements of different stiffnesses and geometries, the numerical data are sensitive to these parameters. Moreover, the deflections at different locations from the load are correlated only very approximately. This observation is evident from Figure 6, which shows that the deflection ratios at a typical frequency employed in practice (25 Hz) are sensitive to both geophone location and layer geometry. Whereas for thick pavement the deflection ratios are virtually equal at all geophones, the static displacement exceeds the dynamic displacement by approximately 30 percent. Consequently, pavement moduli would be overestimated by a similar margin if deflection data were analyzed by a static analysis. Such an analysis of pavement deflections for the thin pavement (Figure 8) raises greater difficulties because the deflection ratios are not the same for each geophone. In most iterative-solution schemes, the stiffness of the subgrade, which is assumed to be primarily a function of the deflection at the outermost geophone, would be underestimated by approximately 35 percent in this case. The relatively low deflection ratios at the geophones nearest the Road Rater would in consequence yield anomalously high moduli for the upper pavement layers (despite the virtually identical static and dynamic deflections for these geophones).

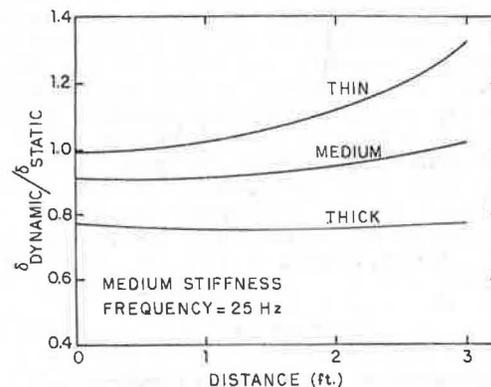


FIGURE 8 Dynamic-to-static surface deflection ratios at various geophone locations.

The effect of pavement stiffness on the dynamic response of pavements is shown in Figure 9. The plots for the soft, medium-stiff, and stiff pavements exhibit similar trends. Most noteworthy is that the peak deflection ratios (at resonance) are virtually the same for each of the three pavements, but the resonance frequencies are distinctly different. Examination of the data reveals that these resonant frequencies are proportional to the square root of the pavement stiffness and are, therefore, proportional to the wave velocities. Figure 10 shows the effect of the depth of subgrade on the dynamic response of the pavement. If the subgrade is shallow, marked resonances may occur and the dynamic deflections may greatly exceed those obtained under static loading conditions. The fundamental frequency when the first resonant mode is excited is almost inversely proportional to the depth of the subgrade, which lends credence to the supposition that resonance occurs principally in the subgrade. The deflection ratios at resonance are greatest for the most shallow subgrade. Clearly, at resonance a static analysis of deflection data will yield erroneous results. In practice, if a resonance condition is suspected, perhaps because of fluctuating geophone readings (9), then the Road Rater's frequency of excitation can be changed by the field operators. However, as Figure 10 shows, because the deflection ratios are unity at only one frequency, selection of an arbitrary frequency of operation will not in general prove satisfactory. Finally, it is worth noting that second harmonics are excited at frequencies approximately twice that of the fundamental. These resonances are, however, relatively small.

As a working hypothesis, the evidence of Figures 9 and 10 suggests that resonance occurs when the frequency of excitation of the Road Rater satisfies the semiempirical equation:

$$f = 0.4 C_s/H \tag{7}$$

where  $H$  is the thickness of the subgrade and  $C_s$  is the shear wave velocity of the subgrade.

If the frequency of excitation of the Road Rater is increased by 50 percent above the resonant frequency, obtained either by means of Equation 7 or by field observation, then the dynamic displacements measured at this higher frequency correspond closely to the static displacement, at least for the range of pavement structures considered in this study. Figures 11 and 12 are plots of the in-phase and 90-degree out-of-phase displacements relative to the Road Rater loading cycle for a typical pavement. The data are plotted as components of the complex amplitude of the deflection ( $u^*$ ) in which the real part  $Re(u)$  signifies the in-phase displacement and the imaginary part  $Im(u)$  signifies the out-of-phase displacement. Clearly, at low frequencies, the out-of-phase displacements are zero. The trend of the data is the same for all geophones (resonance occurs at approximately 11 Hz) but at high frequencies the geophones' responses become increasingly out-of-phase not only with the load but also with each other, which is manifested by differences in the ratios of  $Im(u)$  to  $Re(u)$  among the geophones. In reality, this implies that the wavelength of the surface waves generated by the Road Rater at high frequencies is of the same order of magnitude as the separation of the geophones. Therefore, only at low

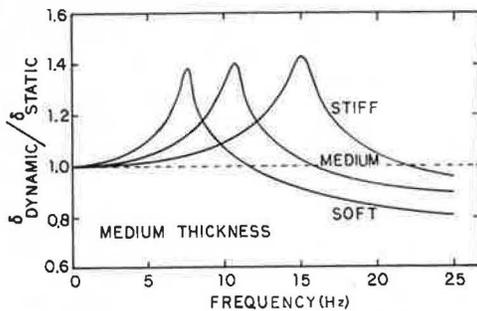


FIGURE 9 Influence of pavement stiffness on the pavement resonant response recorded at geophone 1.

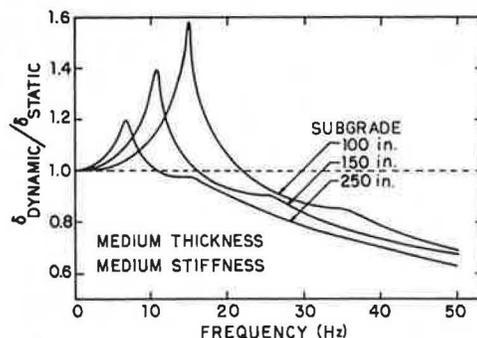


FIGURE 10 Influence of subgrade thickness on the pavement resonant response recorded at geophone 1.

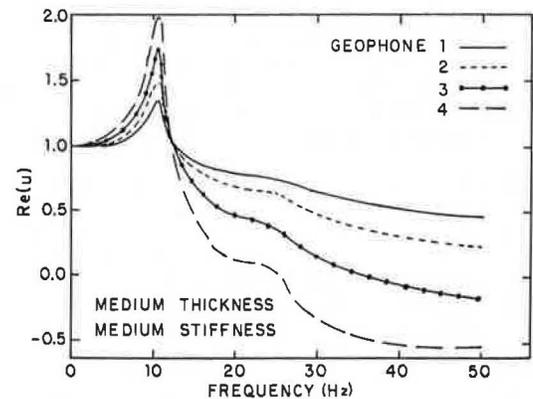


FIGURE 11 In-phase components of displacement.

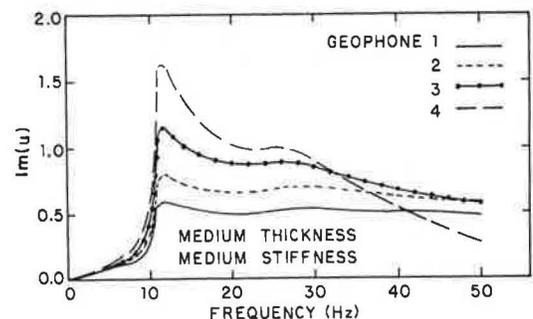


FIGURE 12 Out-of-phase components of displacement.

frequencies, or under static loading, is the notion of a dish-shaped deflection basin valid.

#### DISCUSSION

The numerical results of this study indicate that the response of pavements to dynamic loading may be significantly different from their response to static loading. These differences are principally the result of the inertial forces that resist the motion of the pavement and, at certain frequencies, excite resonances, not the result of the dynamic properties of the pavement materials themselves. Because static analyses cannot be used to predict these phenomena, back-calculation of the stiffness of pavement materials from deflection measurements gained under dynamic loading conditions should be undertaken with caution. Unfortunately, there does not appear to be any simple procedure for determining the deflection ratios as a function of frequency of excitation, pavement stiffness and geometry, and geophone location. Even for a given pavement, the deflection ratios are not the same at each geophone. The evidence suggests that deflection ratios tend to increase with increasing subgrade stiffness and decreasing pavement stiffness but tend to decrease at high frequencies (beyond the resonant frequency). The latter trend is simply a consequence of the inertial forces that increase rapidly with increasing frequency.

Perhaps the most interesting result obtained from this study is the observation that resonances may be excited in the subgrade. At or near these resonant frequencies, the dynamic deflections may be substantially higher than the corresponding static deflections. Thus, at some higher frequency, because the deflection ratios tend to decrease with increasing frequency, the dynamic and static deflections become equal. As a consequence, under these conditions a static analysis of the dynamic deflections will yield the correct values of the pavement layer stiffnesses. As a good first approximation it can be assumed that resonance occurs simultaneously at all geophones although this is not a necessary assumption.

On the basis of this study, it would appear reasonable to suggest that Road Rater deflection measurements should be secured at a number of different frequencies in order to determine the displacement-frequency response. From these data it should be possible to make a good estimate of the static deflection response. The evidence of this study suggests that a frequency of excitation 50 percent higher than the resonant frequency will yield deflection ratios of unity, but caution should be exercised in applying this result in practice because field conditions obviously depart in many ways from the idealized model analyzed here. Devices such as the Dynaflect, which operates at a fixed frequency (8 Hz) and cannot offer the flexibility necessary to explore the frequency response of pavements, should be used with caution.

#### CONCLUSIONS

Pavement deflections generated by such vibratory loading devices as the Road Rater may be substantially different from those obtained under static loading conditions.

Static analyses of dynamic pavement deflections may yield misleading results if the operating frequency of the loading device is approximately equal to the resonant frequency of the pavement system or is so high that inertial forces become dominant.

Resonance arises principally in the subgrade and may be quite marked if the subgrade is shallow. In practice, a resonant condition may be detected in extreme cases by unsatisfactory operation of the data acquisition devices although, more generally, deflection frequency plots may be constructed for this purpose.

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## Dynamic Interpretation of Dynaflect and Falling Weight Deflectometer Tests

JOSE M. ROESSET and KO-YOUNG SHAO

### ABSTRACT

The Dynaflect and the falling weight deflectometer are commonly used for non-destructive testing of pavements. In both cases a dynamic load is imparted, and the determination of the mechanical properties of the pavement, the base, and the subbase is normally performed by comparing the measured deflections at various points along the surface to results of static analyses that consider the subbase as a homogeneous, elastic half-space. In this paper, the displacements obtained from dynamic analyses are compared to those provided by conventional static programs when the subbase is a homogeneous soil stratum of finite depth resting on a much stiffer rocklike material and when the soil properties increase smoothly with depth, as is often the case. The results of these comparisons indicate that for certain ranges of depth to bedrock a static interpretation of the Dynaflect and falling weight deflectometer tests may lead to substantial errors. Situations in which these errors are important are more likely to be encountered with the Dynaflect than with the falling weight deflectometer.

The Dynaflect and the falling weight deflectometer are commonly used for nondestructive testing of pavements. The Dynaflect consists of a force generator and five geophones housed in a small trailer, which is towed by a light vehicle. The loading system consists of two counterrotating eccentric masses. The resulting vertical force varies harmonically with time. At a frequency of 8 Hz, a 1,000-lb peak-to-peak oscillating force and a base load of 1,000 lb are transmitted to the pavement through the loading wheels. The resulting deflection basin is measured by five geophones that are mounted on the trailer draw bar at 12-in. intervals. The positions of the geophones (ST1 through ST5) with respect to the wheels are shown schematically in Figure 1.

The falling weight deflectometer has a 330.7-lb (150-kg) weight mounted on a vertical shaft and housed in a compact trailer that can easily be towed by most conventional passenger cars. The weight is hydraulically lifted to a predetermined height (ranging from 0 to 15.7 in. or 0 to 400 mm). It is then dropped onto a rubber pad 11.8 in. (300 mm)

thick, that helps to distribute the load uniformly over the loading area. The resulting load is a force impulse with a duration of approximately 30 msec and a peak magnitude ranging from 9 to 14,000 lbs (0 to 60 000 N) depending on the drop height. The peak force and maximum deflections at various points along the surface are measured by load cells and velocity transducers. The applied pressure is measured in kilopascals and the deflections in micrometers.

In the case of the Dynaflect the deflections measured at the various stations represent the amplitudes of the steady-state displacements at a given frequency (8 Hz). For the falling weight deflectometer they are the peak displacements under a transient-type excitation. In both cases the tests are dynamic in nature, but the interpretation of their results to estimate the elastic properties of the pavement, base, and subbase relies on static analyses. Furthermore, these analyses assume that the soil in the subbase is an elastic, homogeneous, and isotropic half-space. In many cases soil properties