Pavement–Falling Weight Deflectometer Interaction Using Dynamic Finite-Element Analysis

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In almost all linear elastostatic programs used in backcalculation procedures, a uniform pressure distribution is assumed for the applied load. As such, the loading system of any falling weight deflectometer (FWD) should be designed so that the load transferred to the pavement is uniform. This is difficult because the pressure distribution under the FWD is also affected by the pavement profile being tested. The other aspect of the FWD testing that is typically ignored is the dynamic nature of the load. The dynamic effects are related to the pulse width as well as the variation in the stiffness of the subgrade. A finite-element study has been carried out to investigate the significance of these parameters on the determination of the remaining lives of pavements. Cases where the imparted load would or would not yield a uniform pressure distribution under the FWD plate are identified. An investigation of the effects of the plate-pavement interaction on the static interpretation of the dynamic deflections is presented. The results indicate that the dynamic nature of the load may more significantly affect the deflections measured away from the load, whereas the plate-pavement interaction may affect the deflection of the first sensor. The errors in the estimation of the layer moduli that would be obtained from the standard backcalculation procedures are also determined. The results of this study confirm that the plate-pavement interaction and the dynamic effects are important for the FWD test on flexible pavements.

In almost all falling weight deflectometer (FWD) backcalculation procedures, a uniform pressure distribution is assumed for the applied load. If the assumption of uniform stress distribution is deviated, the deflections of the sensors near the affected loading may be in error (*1*). As such, the backcalculated moduli, critical stresses and strains, and, naturally, the prediction of the pavement life may be in error.

The pavement deflections under a static load may differ from those under an impulse load because of effects such as inertia, damping, and resonance. Previous studies indicate that static analysis of FWD deflection data may, in general, lead to inaccurate estimates of pavement moduli (*2–5*).

The major objective of the study summarized here was to assess the significance of a nonuniform pressure distribution under dynamic loading on the measured and backcalculated parameters. The pressure distribution under the loading plate and the effects of the components of the plate on the results obtained from the FWD were quantified in a previous work by Boddapati and Nazarian (*6*) and will not be repeated here.

Two models were used. In one model, the typical composite FWD loading plate on top of the pavement system was discretized in a finite element mesh; in the other, a uniform load distribution was assumed on top of the pavement. Through sensitivity analyses, the effects of stiffness and thickness of different pavement layers on the response of the pavement were studied. The variations in the measured deflection basin and the critical stresses and strains were discussed and quantified.

Soil properties usually vary with depth, and the soil is underlain at some depth by significantly stiffer material. The presence of bedrock or stiff layers at a finite depth may result in the dynamic amplification of the response (*7*). However, the duration of an FWD impulse is also an important parameter. Considering all the aforementioned problems, an analysis is performed on the dynamic effects of the FWD loading on critical stresses and strains within the pavement.

The goal of this paper is neither to address the analytical and numerical complications of the analysis nor to propose a new algorithm to address these problems. It is, instead, to obtain the numerical results from a complicated and involved process and present them as a guide for those involved in the FWD testing. Although the results are not substantiated by fieldwork, they qualitatively demonstrate the reasons for some of the persistent problems encountered in matching deflection basins. The results are presented to initiate a dialogue, and, it is hoped, to lead to future research to verify the results and to further development to resolve them.

BACKGROUND

Deflection basins from dynamic loading differ in several respects from the deflection basins from static analysis. A rigorous elastodynamic analysis of the FWD indicates that the inertia of the pavement is instrumental in the displacement response of the pavement. Mamlouk and Davis (*2*) and Shao et al. (*4*) incorporated inertial effects into a rigorous elastodynamic analysis of pavement response and have indicated that these effects are significant.

Kang (*8*) developed a mathematical model that could take into account not only the dynamic nature of the loads, but also the variation of material properties in the soil-pavement system.

Little attention has been focused on the distribution of load under the FWD plate. Uzan and Lytton (*1*) conducted an analytical study that indicated the consequences of a nonuniform pressure distribution under the FWD load. However, they made no attempt to quantify the distribution of the stress.

Shahin et al. (*9*), using stress-sensitive film, demonstrated that the stress distribution is in some instances nonuniform. However, they did not quantify the effects that the stress distribution may have on the response of the pavement.

Boddapati and Nazarian (*6*) numerically demonstrated that the stress distribution under the FWD plate is reasonably uniform for

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rigid pavements; for flexible pavements, the stress distribution is influenced by the plate-pavement interaction. The thickness of the polyvinyl chloride (PVC) and steel plates and the rubber pad used in the construction of the FWD affect the deflection basin. The most significant parameter was found to be the stiffness of the rubber pad.

OVERALL APPROACH

Deflection basins from three sets of numerical cases were compared. The first set, the control case, corresponded to the elastostatic case with a uniform load applied to the pavement surface. For simplicity, these results will be referred to as STATUNFRM, which stands for static condition with uniform load distribution. This represents the algorithm normally used in the backcalculation procedure. The second set, DYNUNFRM, corresponded to the case where the dynamic nature of the load was considered but the FWD-pavement interaction was ignored (a uniform load was assumed). For the last set, DYNFWDINT, both the FWD-pavement interaction and the dynamic nature of the load were considered. In this manner, the dynamic effects can be determined by comparing the results from STATUNFRM and DYNUNFRM. The influences of the FWD-pavement interaction can be similarly delineated by comparing the DYNUNFRM case with the DYNFWDINT case.

Sensitivity analyses were also performed. In these analyses, the stiffness and thickness of each pavement layer were varied several times to determine the influence each had on the FWD-pavement interaction. In the following sections, the pertinent details and results are presented.

Physical Model

The composite loading plate of FWD was assumed to consist of a steel plate having an elastic stiffness of 70 GPa and a Poisson's ratio of 0.3 over a PVC plate having an elastic stiffness of 7 GPa and a Poisson's ratio of 0.3. The diameter of the FWD loading plate was assumed to be 300 mm, with a 25-mm-diameter hole at the center. The steel and PVC plates rest over a rubber pad having an elastic stiffness of 35 MPa and a Poisson's ratio of 0.49. Steel and PVC plates were assumed to be 25 mm thick, and the rubber pad, 6 mm thick.

The sensitivity analyses were conducted using a standard pavement section as the control pavement section. The standard pavement section was assumed to have three layers: an asphalt concrete (AC) layer over a granular base over a subgrade. The thickness of the AC and base layers were assumed to be 75 mm and 300 mm, respectively. The moduli of the AC, base, and subgrade were assumed to be 3 500 MPa, 350 MPa, and 70 MPa, respectively. The Poisson's ratio of the AC and base layers was assumed to be 0.35. A Poisson's ratio of 0.45 was assigned to the subgrade.

For dynamic analyses, a half-sinusoidal load was assumed to affect the composite loading plate of an FWD. The duration of the simulated impulse loading was 40 msec, with the peak load at 20 msec. The response of the pavement was observed for 250 msec. The peak stress was assumed to be 930 kPa.

Finite-Element Model

The program ABAQUS, developed by Habbit, Karlsson and Sorensen, Inc., was used throughout this study. The problem was assumed to be axisymmetric in nature. The characteristics of the finite-element mesh were carefully selected to ensure accurate results. The lateral boundaries were placed about 12 m from the center of the load. To determine the stress distribution under the plate, a well-refined mesh along the interface of the plate and pavement surface was necessary. As a result, a minimum of about 7,500 elements were used in this study. With such a mesh, the maximum difference between the results from the finite-element program and known cases was less than 1 percent (*10*). In addition, for dynamic executions, appropriate absorbing boundaries were incorporated to minimize any reflection of energy into the model region.

All materials were considered to be linear-elastic, homogeneous, and isotropic. Some of these assumptions may be invalid in some actual field cases. However, because the results presented in the following section are comparative, the deviation from these assumptions may only slightly affect the generality of the conclusions.

RESULTS

The deflection basins resulting from the control condition (STATUNFRM), dynamic condition (DYNUNFRM), and dynamic-with-interaction case (DYNFWDINT), using the standard pavement profile previously described, are compared in Table 1. Except under the loaded area, deflection basins calculated using both dynamic algorithms are similar. These similarities in deflections confirm that the FWD-pavement interaction has little effect on the deflections of sensors that are away from the loading plate.

On the other hand, large variations between the deflections from the static and dynamic algorithms are observed. The variation is small for a sensor located about 30 cm from the load (about 3 percent); it increases to about 50 percent for a sensor located about 180 cm from the load. These differences emphasize the importance of considering the dynamic nature of the FWD loads.

Under the load, on the other hand, the static and dynamic conditions having a uniform loading yield similar deflections. However, as soon as the FWD-pavement interaction is considered, the central deflection differs by about 5 percent. This exhibits the importance of the FWD-pavement interaction. Even though the difference is small, it will significantly affect the backcalculated moduli (see next section). Based on this discussion and for the sake of brevity, only the deflections from DYNFWDINT are compared with those of the STATUNFRM.

In the next sections, these types of comparisons will be carried out to demonstrate and delineate the dynamic effects as well as the FWD-pavement interaction.

Sensitivity Study

Asphalt Layer

To compare the results from the static and dynamic analyses, two cases are presented. In one, the stiffness of the asphalt layer was varied from 1.75 GPa to 7 GPa. In the other, the thickness of the AC layer was varied from 25 mm to 125 mm.

Asphalt Modulus The differences in the deflection basins calculated from DYNFWDINT and STATUNFRM algorithms as a function of the modulus of the AC layer are presented in Table 2. As indicated in Table 1, for the standard pavement section (modulus of 3.5 GPa), the differences in deflections vary from 3 to about

TABLE 1 Dynamic and Static Deflections Calculated From Different Analyses for Control Pavement Section

Radial Distance (cm)	Deflections Calculated by				
	STATUNFRM (microns)	DYNUNFRM (microns)	Variation*1 percent	DYNFWDINT (microns)	Variation*2 percent
(1)	(2)	(3)	(4)	(5)	(6)
0	884	889	-0.6	836	5.3
30	550	568	-3.3	568	-3.2
60	349	375	-7.4	375	-7.4
90	238	269	-13	269	-13
120	167	202	-21.3	202	-21.3
150	120	160	-33.3	160	-33.3
180	88	133	-51.0	133	-51.0

*1 Variation = [(Column2 - Column3) / Column2] * 100
*2 Variation = [(Column2 - Column5) / Column2] * 100
STATUNFRM = Static condition with a uniformly distributed load
DYNUNFRM = Dynamic condition with a uniformly distributed load
DYNFWDINT = Dynamic condition when FWD/pavement interaction is considered

51 percent. For the other two AC stiffnesses, the differences in the deflections are similar to the standard one. Therefore, it can be concluded that the modulus of the asphalt layer has minor influences on the variation in deflection basins under the static and dynamic loads.

Inspecting the differences between the central deflections obtained from the two approaches, one can conclude that the FWD-pavement interaction is affected somewhat by the modulus of the AC. As the modulus of the AC increases from 1.75 to 7 GPa, the difference between the two dynamic deflections decreases from 8 to 3 percent. Therefore, the stiffer the AC layer is, the less significant the FWD-pavement interaction will be.

Thickness The differences in the deflection basins calculated by STATUNFRM and DYNFWDINT constantly decrease as the thickness of the AC layer increases (see Table 2). As the thickness of the AC increases from 25 to 125 mm, the difference between the central deflections from the STATUNFRM and DYNFWDINT decreases from 11 to 2 percent.

Base Layer

To find the influence of the base layer on the dynamic response of a pavement system, its thickness and stiffness were perturbed. The stiffness of the base layer was varied from 88 to 1400 MPa, and the thickness was varied from 150 to 450 mm.

Modulus The differences in the deflection basins calculated by DYNFWDINT and STATUNFRM are largely influenced by the base stiffness (see Table 3). The higher the stiffness of the base layer is, the smaller the differences in deflections calculated by DYNFWDINT and STATUNFRM will be.

The differences between the central deflections calculated by DYNFWDINT and STATUNFRM decreased from 8 to 3 percent as the stiffness of the base layer increased from 88 to 1 400 MPa.

The differences between the static and dynamic deflection basins become less significant. For example, the differences in the deflections for the sensor located 180 cm from the load decrease to 32 percent from about 70 percent as the modulus increases from 88 to 1 400 MPa.

Thickness The thickness of the base layer has a limited influence on the differences in the central deflections (see Table 3). Therefore, the FWD-pavement interaction is not sensitive to the thickness of the base.

On the other hand, it appears that the dynamic effects are influenced by the thickness of the base. The differences in deflections obtained by the dynamic and static approaches decreased from 69 to 37 percent as the thickness of the base increased from 150 to 450 mm.

Subgrade

The stiffness of the subgrade was varied from 17.5 to 280 MPa. The variation in the deflection, as a function of radial distance for different stiffnesses of the subgrade, is shown in Table 4. The differences between the two approaches (DYNFWDINT and STATUNFRM) are largely influenced by the stiffness of the subgrade. For a

TABLE 2 Influence of Asphalt Layer on Deflection Basins

Layer Modulus

AC Modulus (MPa)	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1250	STAT-UNFRM	950	555	350	238	165	118	85
	DYN-FWDINT*	878 (8)	575 (-4)	378 (-8)	270 (-14)	200 (-23)	158 (-35)	133 (-54)
7000	STAT-UNFRM	790	530	340	233	165	118	88
	DYN-FWDINT*	765 (3)	543 (-3)	363 (-7)	263 (-12)	198 (-20)	158 (-32)	130 (-49)

Layer Thickness

AC Thickness (mm)	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
25	STAT-UNFRM	1130	588	363	238	163	115	83
	DYN FWDINT*	1008 (11)	613 (-4)	393 (-8)	273 (-15)	200 (-25)	160 (-39)	133 (-59)
125	STAT-UNFRM	688	488	330	230	165	120	90
	DYN-FWDINT*	670 (2)	500 (-3)	350 (-6)	258 (-11)	198 (-19)	158 (-29)	130 (-45)

Numbers in Parentheses Denote Percent Difference from Results Obtained using STATUNFRM and DYNFWDINT
* Difference = [(STATUNFRM - DYNFWDINT) / STATUNFRM] * 100
All deflections are in microns

subgrade with a very low stiffness (17.5 MPa), the deflections calculated by STATUNFRM were always higher. The differences decreased from 20 to 5 percent as the radial distance from the load increased from 0 to 180 cm. As the subgrade stiffness increased to 280 MPa, the variation in the deflection calculated at 180 cm increased to 56 percent.

Stiff AC and base layers over a 17.5 MPa subgrade can be modeled as a foundation on a weak base. This increases the difference between the fundamental frequency of the pavement and that of the impulsive force, which in turn decreases the peak deflections, compared with those of STATUNFRM. Therefore, the difference between the deflections obtained by the STATUNFRM and DYNFWDINT is positive and decreases from 19.6 to 4 percent. As the subgrade stiffness increased to 280 MPa, the differences varied between 5 and −56 percent (negative sign indicates higher dynamic deflections).

Depth to Rigid Base

Two main parameters that influence dynamic deflections are the natural frequency of the pavement system and the frequency content of the FWD impulse. The natural frequency of the pavement system is directly related to the stiffness of the paving layers and depth to a rigid base (if present). The stiffer the pavement system or the closer the rigid layer to the surface is, the higher the natural frequency will be. The frequency content of the impulse is directly related to the duration of the impulse. The longer the impulse width is, the more energy will concentrate toward lower frequencies. The interaction of these two parameters is studied here.

Data file DYNFWDINT was executed for depths to the rigid base varying from 1.9 to 7.5 m. A 50 percent decrease in depth to the rigid base (from 7.5 to 3.8 m) only slightly influenced the peak amplitude under the load. A further decrease in the depth to the rigid base (to 1.9 m) resulted in a much more significant decrease in the deflection.

When a depth to bedrock of 3.8 m was used, the differences in static (rigid base at 7.5 m) and dynamic deflections increased from 6 to 14 percent.

A further decrease in the subgrade thickness influenced the deflection basins for two reasons. First, the decrease in the subgrade thickness increases the fundamental frequency of the pavement, and thus the energy associated with the impulsive force input. Second, the

TABLE 3 Influence of Base Layer on Deflection Basins

Layer Modulus

Base Modulus (MPa)	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
88	STAT-UNFRM	1490	825	388	225	150	108	80.0
	DYN-FWDINT*	1375 (8)	855 (-4)	430 (-11)	273 (-21)	200 (-34)	160 (-50)	135 (-70)
1400	STAT-UNFRM	510	380	293	223	170	128	95
	DYN-FWDINT*	500 (3)	388 (-2)	305 (-4)	240 (-8)	190 (-11)	155 (-21)	128 (-32)

Layer Thickness

Base Thickness (mm)	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
150	STAT-UNFRM	1110	693	388	235	155	108	80
	DYN-FWDINT*	1060 (5)	720 (-4)	425 (-9)	278 (-18)	200 (-30)	160 (-48)	135 (-69)
450	STAT-UNFRM	748	448	298	218	160	120	93
	DYN-FWDINT*	695 (7)	455 (-2)	313 (-6)	238 (-10)	188 (-16)	150 (-25)	125 (-37)

Numbers in Parentheses Denote Percent Difference from Results Obtained using STATUNFRM and DYNFWDINT
* Difference = [(STATUNFRM - DYNFWDINT) / STATUNFRM] * 100
All deflections are in microns

decrease in the depth to bedrock results in less material that can be strained. In Table 5, the deflections by STATUNFRM with a rigid base fixed at 7.5 m are also compared with those by STATUNFRM with varying depths to the rigid base. In this manner, the contribution of the dynamic nature of a load to the variation in deflections can be better appreciated. In Table 5, the standard STATUNFRM refers to the standard practice in backcalculation when the depth to bedrock is fixed at an arbitrary depth (7.5 m here).

With the rigid base fixed at 3.8 m, the differences in deflections varied from 6 to 47 percent as the radial distance increased from 0 to 180 cm. A further decrease in the subgrade thickness to 1.9 m increased the difference from 17 to 102 percent.

In general, as reflected in Table 5, the contribution of the dynamic nature of the load to differences in deflections is mixed. In some cases (for depth to bedrock of 3.8 m), the dynamic effects are constructive; that is, the deflections obtained when considering the dynamic effects are closer to those obtained when a static condition and deep depth to bedrock are assumed. In other cases, the dynamic nature of the load adds to the differences between the standard static solutions. This indicates that the derivation of a simple relationship for correcting for depth to bedrock may not be easy.

Pulse Duration

To study the influence of the frequency content of impact, the pulse duration was changed from 20 to about 80 msec. The exercise was repeated for several depths to the rigid base. Typical results are shown in Figure 1.

For a subgrade thickness of 7.5 m, the central deflection calculated by DYNFWDINT with a pulse of 20 msec resulted in a value lower than those calculated for 40 and 80 msec. The trend is illustrated in Table 6 and Figure 1.

A decrease in the subgrade thickness to 3.8 m results in a behavior that differs somewhat from that for a subgrade thickness of 7.5 m (see Table 6). The peak deflection at the center increased as the pulse duration increased from 20 to 80 msec. However, in this case, the deflections from impulses of 20 and 40 msec have changed only slightly, whereas those from the 80 msec are significantly smaller.

As reflected in Table 6, a further decrease in the rigid base thicknesses to 1.9 m resulted in smaller peak deflections. At 180 cm away, the peak deflections decreased with the increase in pulse duration (with the decrease in frequency of impulse). The negative

TABLE 4 Influence of Subgrade Stiffness on Deflection Basins

Subgrade Modulus (MPa)	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
18	STAT-UNFRM	1740	1360	1060	833	650	505	390
	DYN-FWDINT*	1400 (20)	380 (17)	880 (17)	693 (17)	553 (15)	445 (12)	373 (5)
280	STAT-UNFRM	493	208	93	55	38	28	20
	DYN-FWDINT*	455 (8)	220 (-6)	105 (-13)	68 (-21)	50 (-31)	38 (-42)	30 (-56)

Numbers in Parentheses Denote Percent Difference from Results Obtained Using STATUNFRM and DYNFWDINT
* Difference = [(STATUNFRM - DYNFWDINT) / STATUNFRM] * 100
All deflections are in microns

deflections were caused by the heave in the soil at the outermost deflection station.

The deflection bowls resulting from the three pulse widths of 20, 40, and 80 msec for subgrade thicknesses of 7.5, 3.8, 1.9 m, respectively, are compared with those from STATUNFRM for a 7.5-m-thick subgrade. This is done to define the differences between the pavement analysis done ignoring the existence of the bedrock and dynamic effects.

For the case of depth to bedrock at 7.5 m, the differences between the two approaches (STATUNFRM and DYNFWDINT) for pulse widths of 40 and 80 msec varied from 1 to about 52 percent when the radial distance increased from 0 to 180 cm. The pulse width of 20 msec, which contains energy at higher frequencies, caused differences from 15 to about 26 percent as the radial distance increased from 0 to 180 cm. One interesting point is that some of the deflections are overestimated and others are underestimated.

TABLE 5 Influence of Rigid Base Depth on Deflections Measured

Rigid Base Depth, m	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
Standard STATUNFRM		870	543	345	235	165	118	88
7.5	DYN-FWDINT	823 (5)*1	560 (-3)	370 (-7)	265 (-13)	200 (-21)	158 (-33)	130 (-51)
	STAT-UNFRM	870 (0)*2	543 (0)	345 (0)	235 (0)	165 (0)	118 (0)	88 (0)
3.8	DYN-FWDINT	815 (6)	553 (-2)	358 (-4)	248 (-6)	178 (-9)	133 (-12)	100 (-14)
	STAT-UNFRM	820 (6)	493 (9)	295 (14)	188 (20)	118 (28)	75 (37)	45 (47)
1.9	DYN-FWDINT	730 (16)	458 (15)	260 (25)	148 (37)	80 (52)	38 (69)	13 (86)
	STAT-UNFRM	725 (17)	398 (27)	208 (40)	108 (55)	48 (71)	15 (87)	-3 (102)

Numbers in Parentheses Denote the Percent Difference from Results Obtained with STATUNFRM Assuming Depth to Rigid Base of 7.5 m (Standard STATUNFRM)
*1 Difference = [(Std. STATUNFRM - DYNFWDINT) / STATUNFRM] * 100
*2 Difference = [(Std. STATUNFRM - STATUNFRM) / STATUNFRM] * 100
All deflections are in microns

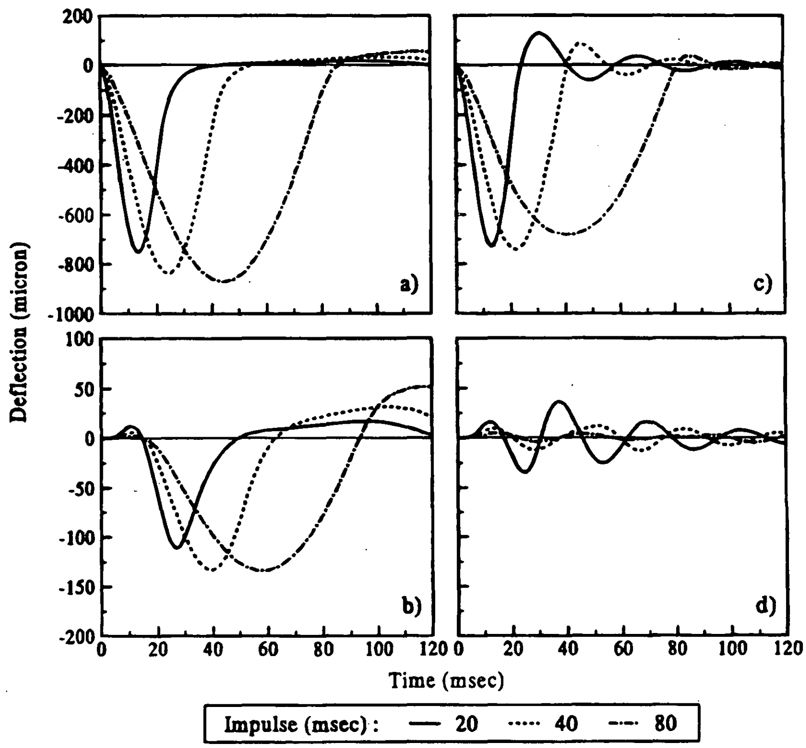

FIGURE 1 Influence of pulse duration on deflection. (*a*) Central deflection for depth to rigid base of 7.5 m, (*b*) deflection at 180 cm for depth to rigid base of 7.5 m, (*c*) central deflection for depth to rigid base of 1.9 m, and (*d*) deflection at 180 cm for depth to rigid base of 1.9 m.

For a pulse width of 20 msec with a subgrade thickness of 3.8 m, a better agreement between the static and dynamic analyses is obtained. The differences are within plus or minus 15 percent. However, in some cases, the deflections are overestimated and in others underestimated. A significant difference exists between this case (depth to bedrock of 3.8 m) and the previous case (depth to bedrock of 7.5 m). When the bedrock was at the depth of 7.5 m, the deflections from the 20-msec impulse were always smaller than those of the 40- and 80-msec impulses. For the shallower bedrock, deflections from the 80-msec impulse are smaller past a radial distance of 120 cm.

Further decreases in subgrade thickness to 1.9 m in DYNFWDINT naturally resulted in smaller deflections compared with those deflections obtained from STATUNFRM with a subgrade of 7.5 m.

When the rigid base was located at 1.9 m, the difference constantly increased from 18, 16, and 23 percent to about 142, 86, and 106 percent with the radial distance increasing from 0 to 180 cm for the pulses of 20, 40, and 80 msec, respectively. In this case, the 80 and 20 msec pulses consistently produce the lowest deflections, clearly demonstrating the importance of the pulse width–bedrock interaction.

For a 3.8-m depth of bedrock, the dynamic loads are, in most cases, constructive. In other words, for this case, the dynamic nature of the load reduces some of the effects of misassuming depth to bedrock. This pattern is true for a depth of bedrock of 1.9 m, except for a long-duration impulse (80 msec when the differences due to dynamic loads and static loads are small).

In summary, in all cases, depths to bedrock and impulse width interact to produce significant difference between the static and dynamic analysis. In some instances, the dynamic nature of the load neutralizes some of the effects associated with ignoring the presence of bedrock. However, in many cases, the errors may still be too large to ignore the dynamic nature of the load and depth to bedrock. Finally, when bedrock is present, the deflections measured by different FWD devices manufactured by different companies may be different.

Influence on Pavement Evaluation

The elastostatic program BISAR was used in this study. A subroutine based on rutting and fatigue failure criteria was developed to calculate the pavement life using the Asphalt Institute procedure. The backcalculated pavement layer stiffnesses, critical stresses, critical strains, and remaining lives of pavement structures are discussed in the following sections.

As indicated before, the dynamic effects were more pronounced at outer sensors. Static interpretation of these results may largely influence the backcalculated base and subgrade stiffnesses.

The backcalculated pavement layer stiffnesses and critical parameters are shown in Table 7. Typically, the backcalculation could not be performed with small basin-fitting errors (the reasons are described later). The mismatches averaged 8 percent, which is large. Based on the experience of the authors, such level of mismatch is not uncommon for flexible pavements. Practically speaking, the

TABLE 6 Influence of Pulse Width on Deflection Basins

Depth to Rigid Base of 7.5 m

Impulse msec	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
Standard STATUNFRM		870	543	345	235	165	118	88
20	DYNFWDINT	740 (15)*2	488 (10)	313 (9)	218 (7)	165 (0)	130 (-10)	110 (-26)
40	DYNFWDINT	823 (5)	560 (-3)	370 (-7)	265 (-13)	200 (-21)	158 (-33)	130 (-51)
80	DYNFWDINT	858 (1)	585 (-8)	390 (-14)	280 (-19)	210 (-28)	163 (-39)	133 (-52)

Depth to Rigid Base of 3.8 m

Impulse msec	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
STATUNFRM		820 (6)*1	493 (9)	295 (14)	188 (20)	118 (28)	75 (37)	45 (47)
20	DYNFWDINT	740 (15)*2	488 (10)	310 (10)	218 (7)	160 (3)	123 (-5)	98 (-13)
40	DYNFWDINT	815 (6)	553 (-2)	358 (-4)	248 (-6)	178 (-9)	133 (-12)	100 (-14)
80	DYNFWDINT	815 (6)	543 (0)	343 (0)	233 (1)	160 (3)	110 (6)	75 (11)

Depth to Rigid Base of 1.9 m

Impulse msec	Method of Calculation	Deflection Measured at (cm)						
		0	30	60	90	120	150	180
STATUNFRM		725 (17)*1	398 (27)	208 (40)	108 (55)	48 (71)	15 (87)	-3 (102)
20	DYNFWDINT	718 (18)*2	460 (15)	270 (22)	163 (31)	95 (42)	55 (54)	-38 (142)
40	DYNFWDINT	730 (16)	458 (15)	260 (25)	148 (37)	80 (52)	38 (69)	13 (86)
80	DYNFWDINT	670 (23)	398 (27)	205 (40)	108 (54)	53 (68)	23 (82)	-5 (106)

Numbers in Parentheses Denote Difference from Results Obtained with Assuming Depth to Rigid Base of 7.5 m (Standard STATUNFRM reported in Table 6a)

*1 Difference = [(Std. STATUNFRM - STATUNFRM) / Std. STATUNFRM] * 100

*2 Difference = [(Std. STATUNFRM - DYNFWDINT) / Std. STATUNFRM] * 100

designer has to face a dilemma: Should the FWD data be discarded or should the results be used in the design? If the data are discarded, substantial effort and funds are wasted. On the other hand, if the data are used, the consequences (at least theoretically) are as follows.

As reflected in Table 7, except in isolated cases, the backcalculated moduli of the AC layer are equal to 28 GPa (upper limit for AC layer modulus assigned to BISDEF), regardless of the asphalt layer stiffness.

For the base layer, the backcalculated moduli are closer to the actual values. Typically, as the pavement structure becomes stiffer, the base modulus is more accurately predicted. The base modulus (except in a few cases) is underestimated, possibly

TABLE 7 Influence of Different Pavement Profiles on Backcalculated Parameters and Remaining Lives

Parameter	Moduli (MPa)			Thickness (mm)		Backcalculated Moduli (MPa)			Avg. Basin Fitting Mismatch (percent)	Remaining Life (million ESAL)	
	AC	Base	Sub grade	AC	Base	AC	Base	Sub grade		Rutting	Fatigue
Standard Pavement	3500	350	70	75	300	6664 (-90)*	329 (6)	72.1 (-3)	0.7	2.4 (-200)	2.4 (-24)
AC Modulus	1750					28000 (-1500)	245 (30)	54.6 (22)	9.5	2.4 (-200)	2.4 (-54)
	3500	350	70	75	300	28000 (-700)	280 (20)	55.3 (21)	8.7	2.9 (-165)	2.8 (-118)
	7000					28000 (-300)	343 (2)	56.0 (20)	7.4	3.7 (-130)	3.5 (-141)
AC Thickness				25		28000 (-700)	490 (-40)	56.0 (19)	8.0	0.7 (-101)	2.5 (88)
	3500	350	70	75	300	28000 (-700)	280 (20)	55.3 (21)	8.7	2.9 (-165)	2.8 (-118)
				125		9430 (-169)	287 (18)	56.7 (19)	7.1	6.7 (-63)	4.3 (-52)
Base Modulus		87.5				28000 (-700)	71 (19)	52.5 (25)	8.7	1.8 (-722)	1.0 (-910)
	3500	350	70	75	300	28000 (-700)	280 (20)	55.3 (21)	4.5	2.9 (-165)	2.8 (-118)
		1400				28000 (-700)	1099 (22)	57.4 (18)	3.3	32.7 (-24)	21.2 (87)
Base Thickness					150	28000 (-700)	183 (48)	55.3 (21)	11.6	0.8 (-610)	1.4 (-95)
	3500	350	70	75	300	28000 (-700)	280 (20)	55.3 (21)	8.7	2.9 (-165)	2.8 (-118)
					450	10374 (-196)	399 (-14)	57.4 (18)	4.0	12.2 (-54)	2.8 (-86)
Subgrade Modulus			17.5			28000 (-700)	322 (8)	18.9 (-8)	4.6	0.5 (-416)	2.4 (-87)
	3500	350	70	75	300	28000 (-700)	280 (20)	55.3 (21)	8.7	2.9 (-165)	2.8 (-118)
			280			22650 (-547)	333 (5)	224 (20)	1.1	88.8 (-100)	4.2 (-204)

Numbers in parantheses corresponding to percent differences between actual and backcalculated values
* Diffcrence = [(Actual Value - Backcalculated Value) / Actual Value] * 100

to compensate for the overestimation of the modulus of the AC layer.

In all cases, the subgrade moduli are underpredicted by about 10 to 20 percent, indicating that the modulus of the subgrade is accurately predicted. This phenomenon is counterintuitive given the large differences between the dynamic and static deflections for the outer sensors (see Tables 2, 3, and 4). From a careful inspection of the deflections from any case presented in Tables 3 through 5, one will notice that the differences between the dynamic and static deflections become increasingly larger as the distance from the load increases. Deflections from Sensors 3 (radial distance of 60 cm) through 7 (radial distance of 180 cm) contribute significantly to the backcalculation of the modulus of the subgrade. The differences between the dynamic and static deflections of Sensor 3 are typically not more than 10 percent. Therefore, on the average, the differences in the dynamic and static deflections of the sensors contributing significantly to the modulus of the subgrade can be considered to be about 20 percent and as such a subgrade modulus with an accuracy of about 20 percent.

One important lesson to be learned is that estimating the modulus of the subgrade from the last sensors, where the dynamic and static deflections are deviating the most, may not be appropriate. From this discussion, one can observe why the deflection-basin-fitting mismatch is large for most cases reported in Table 7. It is practically impossible to simultaneously achieve close fits for the deflections from the middle sensors (60 and 90 cm) and far sensors (150 and 180 cm). The remaining lives of the pavement are typically overestimated by 2 to 10 times (Table 7). This indicates the importance of considering the FWD-pavement interaction and the dynamic nature of imparted load in the FWD tests.

Pulse Duration

Table 8 presents the effects of the pulse duration on the remaining life. The basin-fitting mismatches were on the average about 8 percent. The backcalculated moduli of the AC layer are constant and equal to 28 GPa, regardless of the pulse duration. The backcalculated base layer moduli are within 20 percent of actual value. For small pulse durations, the subgrade moduli are closely estimated. The differences in backcalculated subgrade moduli and the actual values are increased with the increase in pulse duration. In all cases, the remaining lives by rutting and fatigue are overestimated.

Depth to Rigid Base

For a depth to the rigid base of 3.8 m, the backcalculated modulus of the AC layer is overestimated by a factor of 1.6, whereas the moduli of base and subgrade layers are closely estimated (Table 8). The average basin-fitting mismatch for this case is small. Because of the small variations in the backcalculated moduli of base and subgrade layers to the actual values, the remaining lives by rutting and fatigue are also closely calculated.

A further decrease of depth to the rigid base to 1.9 m resulted in an overestimation of the AC layer modulus by a factor of 8. On the contrary, the modulus of the base layer is underestimated by a factor as high as 10. The backcalculated subgrade modulus is almost four times the actual value. By combining the effects of overestimated and underestimated moduli of AC and base layers, the remaining life by fatigue matches the actual values. High backcalculated moduli of subgrade resulted in a rut life that is almost 24 times higher than the actual value.

TABLE 8 Influence of Relevant Dynamic Characteristics on Backcalculated Moduli and Remaining Lives

Pulse Duration

Pulse Duration (msec)	Backcalculated Moduli (MPa)			Avg.Basin Fitting Mismatch (percent)	Remaining Life (million ESAL)	
	AC	Base	Subgrade		Rutting	Fatigue
(1)	(2)	(3)	(4)	(5)	(6)	(7)
20	28000 (-700)*	294 (16)	67.2 (4)	9.5	4.5 (-315)	3.2 (-142)
40	28000 (-700)	280 (20)	55.3 (21)	8.7	2.9 (-165)	2.8 (-118)
80	28000 (-700)	343 (20)	53.2 (24)	7.4	2.7 (-146)	2.8 (-115)

Depth to Rigid Base

Rigid Base Depth (m)	Backcalculated Moduli (MPa)			Avg.Basin Fitting Mismatch (percent)	Remaining Life (million ESAL)	
	AC	Base	Subgrade		Rutting	Fatigue
(1)	(2)	(3)	(4)	(5)	(6)	(7)
7.5	28000 (-700)	280 (20)	55.39 (21)	8.7	2.9 (-165)	2.8 (-118)
3.8	5720 (-63)	371 (-6)	65.8 (6)	0.8	1.4 (-29)	1.6 (-19)
1.9	28000 (-700)	35 (90)	266 (-280)	14.5	245 (-22172)	1.1 (-15)

Numbers in Parentheses Represent Percentage Difference between Actual and Backcalculated Pavement Parameters.

* Difference = [(Actual Value - Backcalculated Value) / Actual Value] * 100

SUMMARY AND CONCLUSIONS

The influence of the plate-pavement interaction considering the dynamic nature of the FWD load is studied here. An investigation was conducted to assess the significance of these parameters on the measured and backcalculated parameters. Through a sensitivity study, the effects of the stiffness and thickness of different pavement layers on dynamic plate-pavement interaction were studied.

The dynamic nature of the FWD load is also considered, and the calculated deflection basins as a function of pavement strength parameters are compared with those calculated by elastostatic analysis. Under dynamic loads, the deflections at a given point are influenced by several parameters. Two of these parameters consist of the natural frequency of the pavement system and the frequency content of the FWD impulse. The natural frequency of the pavement system is directly related to the stiffness of the paving layers and depth to the rigid base (if present). The frequency content of the impulse is directly related to the duration of the impulse. The interaction of these parameters are also studied here.

On the basis of the results presented, the following conclusions can be drawn.

- Deflections measured on flexible pavements can be significantly influenced by the FWD-pavement interaction.
- Stiffer pavements are less influenced by the plate-pavement interaction.
- The dynamic nature of the load significantly affects the deflections measured away from the load.
- For typical pavements, base layer stiffness and thickness (to a lesser extent), as well as subgrade stiffness, influence the pavement response to dynamic loads.
- Depth to bedrock and the duration of impulse interact to produce significantly different static and dynamic deflections. Both factors should be considered.
- When the bedrock is present, the deflections measured by different FWD devices with different pulse durations may be different.
- If the dynamic FWD-pavement interaction is not considered, the remaining lives will be significantly overestimated.

ACKNOWLEDGMENT

This work was supported by the Center for High Performance Computing (CHPC) of the University of Texas System. The financial support and technical advice obtained from CHPC are appreciated.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.