flection bulb) may lead to erroneous estimates of the elastic moduli.

ACKNOWLEDGMENTS

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Pavement Evaluation Using Deflection Basin Measurements and Layered Theory

ALBERT J. BUSH III and DON R. ALEXANDER

ABSTRACT

Recent developments through research efforts at the Waterways Experiment Station (WES) have produced a pavement evaluation procedure that uses deflection basin measurements from nondestructive test devices. These deflections are input for a layered elastic program (BISDEF) that predicts elastic moduli for each pavement layer for up to a four-layer system. The approach has been verified through comparison of predicted moduli from the computer program to moduli from laboratory modulus tests. The moduli determined from the deflection basin and BISDEF are then used with limiting strain criteria and a layered elastic program (AIRPAVE) to determine allowable aircraft loads, strengthening overlay requirements, and so forth. The use of a single evaluation procedure that employs test results from six different nondestructive testing devices to determine the allowable aircraft load on flexible airfield pavements is evaluated. Test data presented here were obtained from a side-by-side comparative study conducted in October 1982 at MacDill Air Force Base on three different pavements (two asphalt concrete and one composite of asphalt concrete over portland cement concrete). Test devices considered in this paper are the WES 16-kip vibrator, three falling weight deflectometers, a Road Rater, and a Dynaflect. Allowable loads determined using data from each device compare favorably with the standard evaluation procedure. The moduli values for the base course materials are higher when a preload is applied as in the case of the WES 16-kip vibrator.

The U.S. Army Engineer Waterways Experiment Station (WES) has been performing research in nondestructive pavement evaluation since the early 1960s. The procedures for evaluating load-carrying capacity have used data collected from a single device, the WES 16-kip vibrator. This device is unique and not presently available in the private sector. A need exists for an evaluation procedure that is device independent.

Nondestructive testing (NDT) offers many advantages over conventional pavement evaluation testing. The main advantage is the ability to collect data at many locations on a runway or taxiway in a short time. Ample test results can be collected in a few hours instead of the day or more required for test pit construction and repair. Nondestructive testing can be conducted at night to provide the least interference with traffic, or in some cases between aircraft operations on a particular airport feature, thus reducing costly delays in airline operations normally associated with test pits.

During the past 20 years several types of NDT equipment have been developed and used in the evaluation of roads and airfields. Most equipment applies a load, either vibratory or impulse, to the pavement and measures the resulting pavement surface deflection. Deflection is obtained with most devices by integrating the surface velocity measured with velocity transducers. The force generators for the vibratory equipment are either counterrotating masses or electrohydraulic systems that produce a sinusoidal loading. The impulse load devices use a falling weight dropped on a set of cushions to dampen the impulse for a loading time to simulate a moving wheel. The magnitude of the load is measured on some devices and calculated on others.

A study was conducted to evaluate the use of a single evaluation procedure employing the results from six nondestructive testing devices to determine the allowable aircraft load on flexible airfield pavements. Results on three pavement areas will be compared. Results will be presented to illustrate the applicability of the layered elastic evaluation procedure for those devices. Comparisons of allowable aircraft loads determined from NDT and destructive evaluation procedures will be presented.

ANALYTICAL MODEL AND APPROACH

A nondestructive evaluation procedure using a layered elastic method of analysis has been developed by WES for light aircraft pavements (1). The reported procedure used only one device, the Model 2008 Road Rater. In this method, a computer program developed to backcalculate the modulus for the measured deflections, CHEVDEF, uses the Chevron (2) layered elastic program. Chevron does not allow variable interface conditions. Therefore, a program called BISDEF, which uses the BISAR (3) program as a subroutine, was developed to handle multiple loads and to consider different layer interface conditions. This procedure is device independent. The routine for determining the modulus values is the same as that presented by Michelow (2). To determine the modulus values, the pavement system is modeled as a layered system. Poisson ratios are assumed for each layer. The modulus of any surface layer may be assigned or computed. If assigned, the value will be based on the type of material, or properties of the material, at the time of testing. For example, the assigned modulus will be a function of pavement temperature for flexible pavements. For BISDEF, a range of modulus values is input with an estimated initial modulus value for each layer for which modulus values are to be computed (variable layer). The number of layers with unknown modulus values cannot exceed the number of measured deflections. Best results are obtained when not more than three layers are allowed to vary. A rigid layer is placed 20 ft from the pavement surface.

Figure 1 is a simplified illustration of how the deflection basins are matched. This illustration is

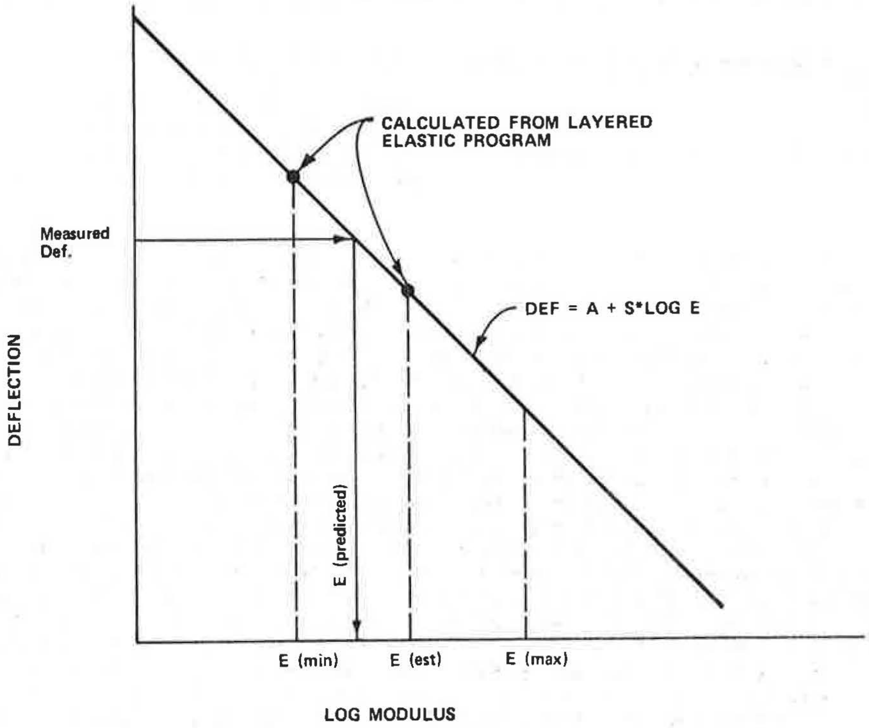

FIGURE 1 Simplified description of how deflection basins are matched in BISDEF.

for one deflection and one layer. For multiple deflections and layers, the solution is obtained by developing a set of equations that define the slope and intercept for each deflection and each variable layer modulus as follows:

$$\mathrm{Def}_j = A_{ji} + S_{ji}(\log E_i) \qquad (1)$$

where

A = intercept,
S = slope,
j = 1 to the number of deflections, and
i = 1 to the number of variable layers.

Errors are minimized by weighting deflections so that the smaller deflections away from the applied load contribute as much as do those near the load. Normally three iterations within the program produce a set of modulus values that yield a deflection basin that is within an average of 3 percent of each of the measured deflections. This accuracy appears to be well within the accuracy of most NDT deflection measuring sensors.

Allowable load-carrying capacities were evaluated using the WES-developed computer program AIRPAVE. For a particular aircraft (gear configuration, load, pass intensity level, and so forth), AIRPAVE uses the modulus values determined from BISDEF and the BISAR program to compute strains (for flexible pavement) that will occur in the pavement system. AIRPAVE then calculates the limiting strain values on the basis of present Corps of Engineers design and evaluation criteria (4,5). The allowable load for the aircraft is determined by comparing the predicted stress or strain to the limiting value.

The horizontal tensile strain at the bottom of the asphalt concrete (AC) and the vertical strain on top of the subgrade are both considered in the evaluation of flexible pavements. The allowable AC strain criterion used is as follows (4):

$$\varepsilon_{\mathrm{All}}(\mathrm{AC}) = 10^{-A} \qquad (2)$$

where

$A = \{N + 2.665\,[\log_{10}(E_{AC}/14.22)] + 0.392\}/5.0$,
$N = \log_{10}$ (aircraft coverages), and
E_{AC} = AC modulus.

The allowable subgrade strains (5) are computed using the following:

$$N = 10{,}000\,[(A/\varepsilon_{\mathrm{All}_{\mathrm{subg}}})^{B}] \qquad (3)$$

where

$A = 0.000247 + 0.000245 \log E_{\mathrm{subgrade}}$,
$B = 0.0658\,(E_{\mathrm{subgrade}})^{0.559}$, and
N = repetitions.

DESCRIPTION OF MacDILL AFB TESTS

WES was sponsored in 1982 by the Air Force Engineering and Services Center (AFESC), Tyndall AFB, Florida, to conduct a study of pavement evaluation techniques based on NDT.

The scope of the project involved comparisons of selected NDT equipment and procedures on representative airfield pavements and a comparison of the NDT results to those obtained from the standard AF evaluation procedures based on test pit measurements. WES selected six private firms with demonstrated NDT capabilities each of which represented a different approach. In addition, WES demonstrated three NDT schemes that it had developed, and the AFESC demonstrated its NDT methodology. The field demonstrations were conducted on five selected test areas at MacDill Air Force Base, Tampa, Florida, during October and November 1982. The test areas at MacDill AFB had been evaluated in March 1980 through test pit measurements in each of the five test areas.

Each participant made an evaluation of the test areas that consisted of determining allowable gross aircraft loadings and overlay thickness requirements and independently submitted a report to WES. A final report (6) presented all test data, a description of each evaluation methodology, and comparisons of the various results. Field test data extracted from this report for six different test devices are presented in this paper. A layout of the airfield at MacDill AFB indicating the five test areas, which consisted of two rigid, two flexible, and one composite pavement, is shown in Figure 2. Results from the two flexible and one composite pavement (Areas 2, 3, and 4) will be presented in this paper.

Description of Test Areas

Each of the test areas contained approximately 50,000 ft² of pavement. This size was selected to be large enough to provide a representative amount of pavement and yet small enough so the five test

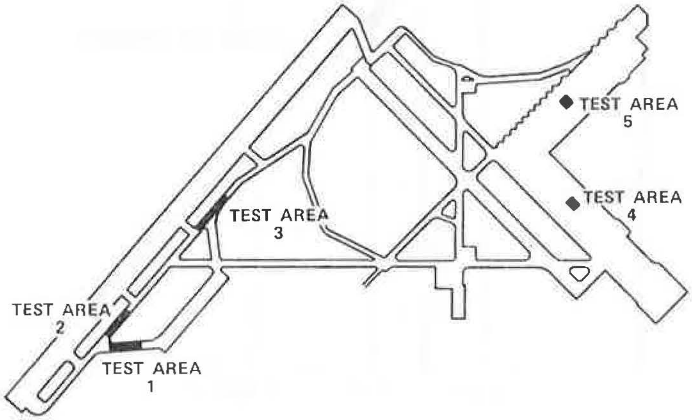

FIGURE 2 Airfield layout at MacDill AFB showing location of test areas.

areas would not require more than 1 full day of testing for each participant. The test areas were selected so as to provide the least interference with MacDill AFB's daily aircraft operations. Each test area was outlined and marked so that the location of all tests could be identified. A summary of the pavement properties as determined by test pit methods for each area is as follows:

Test Area	Pavement Properties
2	10 in. AC 8 in. limerock base CBR = 80 7 in. stabilized subbase CBR = 30 Subgrade (SP) CBR = 30
3	5.5 in. AC 8.0 in. limerock base CBR = 80 7.0 in. stabilized subbase CBR = 30 Subgrade (SP) CBR = 30
4	7.5 in. AC 6.0 in. portland cement concrete (PCC) R = 650 psi Subgrade (SP) k = 250 pci

where

CBR = California bearing ratio,
R = flexural strength of PCC (psi), and
k = modulus of subgrade reaction (pci).

Test Area 2

Test Area 2 was located on the taxiway parallel (Taxiway 3B) to the main runway and was constructed in 1943. The pavement consists of a 10-in. asphaltic concrete surface, an 8-in. limerock base, and a 7-in. subbase of limerock-stabilized sand over the sand subgrade (SP-SM). The pavement was in good condition but contained longitudinal and transverse cracking. This test area was 75 ft wide and 700 ft long.

Test Area 3

Test Area 3 was along the same parallel taxiway as Test Area 2 but farther north. This pavement was also constructed in 1943 and was originally identical to Test Area 2. The original 3-in. asphalt surface had been overlaid to the present thickness of 5.5 in. Beneath the AC surface is an 8-in. limerock base over a 7-in. subbase of limerock-stabilized sand over the sand subgrade. This area, considered in fair condition, exhibited considerable distress in the form of block cracking. This test area was 40 ft by 1,000 ft. The tests were confined to the 40-ft width because the pavement outside this width was not the same thickness.

Test Area 4

Test Area 4 was a composite section located in Apron 1-A-1. The original 6-in. PCC pavement placed on the sand subgrade was constructed in 1941. The slabs were 25 ft by 25 ft, and the design was for 8-in. thickened edges. A 7.5-in. AC overlay was placed on this pavement in 1952 followed by a slurry seal in 1966. There was a considerable amount of reflective cracking of the joints and from cracks in the underlying slabs. The overall condition was considered good. The area was 200 ft by 250 ft.

Description of Test Equipment

The six NDT devices included in this paper are WES 16-kip vibrator, WES falling weight deflectometer (FWD) (15-kip Dynatest Model 8000), 24-kip Dynatest Model 8000 FWD, Shell FWD, Road Rater Model 2000, and Dynaflect. A general description of each is provided in the following paragraphs.

WES 16-Kip Vibrator

The WES 16-kip vibrator is an electrohydraulic steady-state vibratory loading system. The unit is contained in a 36-ft semitrailer along with supporting power supplies and automatic data recording equipment. A 16,000-lb preload is applied to the pavement with a superimposed dynamic load ranging up to 30,000 lb peak-to-peak. The dynamic load can be applied over a frequency range of from 5 to 100 Hertz (Hz), but the standard test frequency is 15 Hz. The dynamic load is measured with a set of three load cells mounted on an 18-in.-diameter load plate. Velocity transducers, which are located on the load plate and at points away from the plate, are calibrated to measure elastic deflection. Test results are recorded on X-Y plotters and a digital printer. Data collected with the WES 16-kip vibrator are the dynamic stiffness modulus (DSM) and deflection basins. DSM is obtained from the slope (load/deflection) of the dynamic load versus deflection data obtained by sweeping the force to maximum at a constant frequency of 15 Hz. This slope is taken at the higher force levels. Deflection basins are obtained by measuring deflections at distances of 18, 36, and 60 in. away from the center of the load plate.

WES FWD

The FWD used by WES was a Dynatest Model 8000 (15 kip). A dynamic force is applied to the pavement surface by dropping a 440-lb weight on a set of rubber cushions, which results in an impulse loading. The applied force and pavement deflections are measured with load cells and velocity transducers. The drop height can be varied from 0 to 15.7 in. to produce an impact force of from 0 to 15,000 lb. The load is transmitted to the pavement through a plate 11.8 in. (30 cm) in diameter. The signal conditioning equipment displays the resulting average pressure in kilopascals and the maximum peak displacement in micrometers. Results presented in this paper were converted to pounds force and mils. Readings from as many as three displacement sensors may be recorded at one time by this data acquisition equipment.

FWD data collected were deflection basin measurements. Displacements were measured on the load plate and at distances of 12, 24, 36, and 48 in. away from the center of the load plate. Because this particular model has only two transducers for deflection basin measurement, the four deflection points were obtained by dropping the weight twice at each location and shifting the transducers to the additional spacings.

Dynatest FWD

The 24-kip Dynatest Model 8000 is a newer version FWD that has several features not found on the WES FWD. The adjustable load was set to its capacity of approximately 24,000 lb, and a loading plate of approximately 6-in. (150-mm) radius was used to simulate the stress level of a heavily loaded jet aircraft. The resulting stress level was somewhat in excess of 200 psi under the loading plate.

The FWD load is transient (as opposed to vibratory), having a time of loading of some 25 to 30 msec, thus corresponding to the effect of a moving aircraft wheel load. Both the load level and a series of seven simultaneous deflections are monitored for each FWD test, with the deflections measured at the surface of the pavement from the center of the loading plate (through a small hole in the middle of it) to a distance of more than 7 ft (2 m) from the center.

Shell FWD

The Shell device is a heavy FWD, and all tests were performed at a force level of 22,400 lb (100 kN). With this machine, a mass falls on a base plate that is connected to a foot plate by means of a set of springs, thus exerting a pulse load on the pavement surface. The duration of the pulse load is comparable to the duration of the pulse load exerted by actual traffic. The force level can be changed by adjusting the drop height. The deflection of the pavement is measured by four velocity transducers (geophones)--on the center of the foot plate and at three other radial distances. At MacDill AFB the radial distances were 0, 24, 39, and 79 in. (0, 60, 100, and 200 cm). The deflection signals are obtained by a single integration of the velocity signals from the geophones, which is performed electronically by integrated circuits.

Road Rater

The Model 2000 Road Rater is a trailer-mounted, electrohydraulic vibrator that has a variable force and frequency capability. A peak-to-peak cyclic load of 4,500 lb at a frequency of 25 Hz can be obtained. Deflection sensors were placed either 12, 24, and 36 in. or 12, 24, and 60 in. from the center of the load plate. One sensor is mounted at the center of the 18-in.-diameter plate.

Dynaflect

The Dynaflect is an electromechanical system for measuring the dynamic deflection of a pavement caused by an oscillatory load. The trailer-mounted device applies a 1,000-lb (4448-N) peak-to-peak sinusoidal load to the pavement. This load is generated by two counterrotating masses that are rotating at a constant frequency of 8 Hz. The force is transmitted to the pavement through two polyurethane-coated steel wheels that are 4 in. (10.2 cm) wide and 16 in. (40.6 cm) in outside diameter. The wheels are spaced 20 in. (50.8 cm) apart. The Dynaflect applies a 2,000-lb (907-kg) static weight to the pavement.

The pavement response to the dynamically applied load is measured with 210-ohm, 4.5-Hz geophones that are shunted to a damping factor of approximately 0.7. One geophone was located directly between the two steel wheels. The other four geophones were spaced at 12-in. (30.5-cm) intervals at the front of the trailer.

A summary of the most important characteristics of each test device and the location of displacement sensors for the MacDill tests is given in Table 1.

Field Tests

The field tests, conducted between October 26 and November 3, 1982, were coordinated with MacDill AFB operations. Each participant in the project was provided a full day to test all five areas. Only one participant was on the field on any given day of the demonstration. Also, each was free to choose the number and location of tests to be performed within each area. However, they were each asked to perform one test at or near a designated location within each area near the test pits. Test Area 4 became the parking apron for F-111 aircraft on November 2. This resulted in much of the area not being available for tests.

Data Analysis

The three test areas at MacDill AFB were evaluated in terms of the Allowable Gross Aircraft Load (AGAL) using deflection data from each of the six NDT devices and the previously described layered elastic methodology. These results were then compared to each other on a relative basis in an attempt to evaluate the device dependency of the procedure. The

TABLE 1 Characteristics of NDT Equipment

	WES 16-Kip	WES FWD	Dynatest FWD	Shell FWD	Road Rater	Dynaflect
Type of load applied	Vibratory	Impulse	Impulse	Impulse	Vibratory	Vibratory
Type of deflection output	Peak-to-peak	Peak	Peak	Peak	Peak-to-peak	Peak-to-peak
Contact area (in.^{2})	254	110	110	110	254	8.6
Peak-to-peak maximum dynamic/impulse force (lb)	30,000	15,000	24,000	22,400	4,500	1,000
Static weight (lb)	16,000	–	–	–	3,800	2,067
Test frequency (Hz)	15	–	–	–	25	8
Loading time (msec)	–	25-30	25-30	–	–	–
Number of displacement sensors	4	3	7	4	4	5
Location of displacement sensors, distance from center of loaded area (in.)						
0	x	x	x	x	x	x
8			x			
12		x	x		x	x
18	x					
24		x	x	x	x	x
36	x	x	x[a]		x[a]	x
39				x		
48		x	x			x
60	x		x[a]		x[b]	
71			x[c]			
79				x		
96			x[b]			

Note: Dashes indicate data were not applicable or were unavailable.

[a] Flexible and composite pavements only.

[b] Rigid and composite pavements only.

[c] Rigid pavements only.

TABLE 2 Deflection Data from Six NDT Devices

Nondestructive Test Device	Force (lb)	Deflection (mils) at Distance from Center of Loaded Area (in.) 0	8	12	18	24	36	39	48	60	71	79	96
Test Area 2													
WES 16-kip	28,960	13.26	–	–	9.18	–	4.480	–	–	2.74	–	–	–
WES FWD	14,206	8.68	–	6.08	–	3.880	2.480	–	1.770	–	–	–	–
Dynatest FWD	23,473	16.30	13.50	11.60	–	7.600	5.100	–	3.600	2.60	–	–	–
Shell FWD	22,400	13.11	–	–	–	6.650	–	3.46	–	–	–	1.69	–
Road Rater	4,510	1.83	–	1.35	–	0.800	0.570	–	–	–	–	–	–
Dynaflect	1,000	0.40	–	0.35	–	0.255	0.207	–	0.177	–	–	–	–
Test Area 3													
WES 16-kip	28,428	24.96	–	–	14.74	–	5.800	–	–	3.96	–	–	–
WES FWD	14,055	23.84	–	14.68	–	5.120	2.580	–	1.870	–	–	–	–
Dynatest FWD	22,043	43.90	31.40	23.40	–	9.800	4.900	–	3.400	2.80	–	–	–
Shell FWD	22,400	37.16	–	–	–	9.960	–	3.94	–	–	–	2.09	–
Road Rater	4,470	4.55	–	3.43	–	1.810	1.180	–	–	–	–	–	–
Dynaflect	1,000	0.90	–	0.60	–	0.380	0.225	–	0.189	–	–	–	–
Test Area 4													
WES 16-kip	28,934	9.80	–	–	8.30	–	5.940	–	–	4.14	–	–	–
WES FWD	14,098	5.09	–	4.57	–	3.860	3.290	–	2.560	–	–	–	–
Dynatest FWD	23,390	8.94	8.35	7.91	–	7.200	5.470	–	–	3.54	–	–	1.89
Shell FWD	22,400	9.80	–	–	–	8.190	–	5.83	–	–	–	3.27	–
Road Rater	3,666	1.23	–	1.22	–	1.000	–	–	–	0.54	–	–	–
Dynaflect	1,000	0.45	–	0.43	–	0.390	0.350	–	0.310	–	–	–	–

Note: Dashes indicate data not applicable.

results were also compared to the results obtained using the standard Air Force evaluation procedure (7). The B-52 (maximum gross load = 490,000 lb) was selected as the design aircraft, and the evaluations of each area were based on 15,000 aircraft passes.

Selection of Deflection Data and Layered Evaluation

To evaluate these pavement areas using the layered elastic methodology, a representative deflection basin for each test area had to be selected for each test device. However, this selection of a representative basin would have been quite complicated for the MacDill data because no two participants used the same test pattern or test frequency. Also, the magnitude of the deflections measured on the flexible pavements varied considerably in the transverse direction across the test areas. Therefore, only the data collected at the one designated location near the test pit in each area were considered in this work. The deflection basins used in determining the layer modulus values for each test area are given in Table 2 and presented graphically in Figures 3-5.

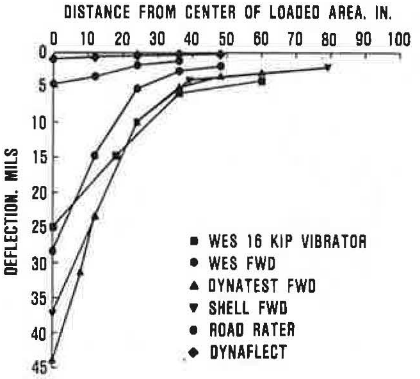

FIGURE 4 Comparison of measured deflection basins on Test Area 3.

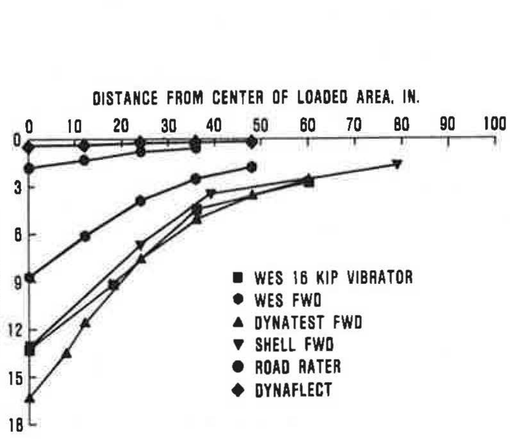

FIGURE 3 Comparison of measured deflection basins on Test Area 2.

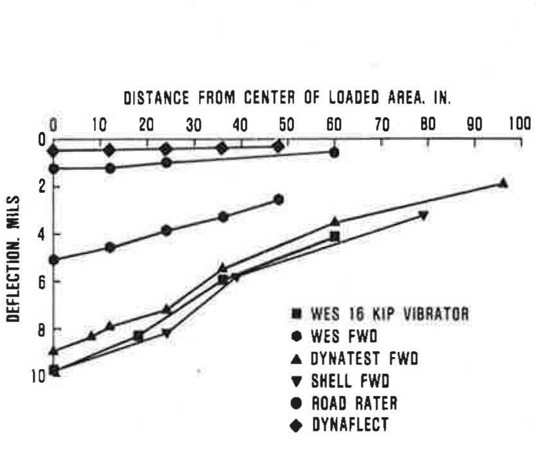

FIGURE 5 Comparison of measured deflection basins on Test Area 4.

These values were input to the computer program BISDEF from which the modulus values were computed for each layer in the pavement system (including the surface AC). Results are summarized in Table 3 for each test area and all six NDT devices. Poisson's Ratios of 0.35, 0.15, 0.35, and 0.40 were assumed for the AC, PCC, base course, and subgrade materials, respectively.

The AGAL was then determined by inputting the base course and subgrade modulus values from BISDEF into the evaluation program AIRPAVE. For evaluation, the modulus values for the AC surface layers were assigned at 300,000 psi. The resulting AGALs are given in Table 4. It is important to note that the composite pavement (Area 4) was evaluated using flexible pavement criteria.

Standard Evaluation

The standard evaluation was performed using the previously stated physical properties for each area. Here, Area 4 was again evaluated as a flexible pavement. The PCC layer beneath the AC was assigned a CBR value of 80. Results of the standard evaluation are given in Table 4.

Analysis of Area 2

A graphic comparison of the modulus values for the base and the subgrade of Area 2 is shown in Figures 6 and 7. The Dynaflect values are high for the limerock base material and low for the subgrade. There is some variability in the values from the other equipment. Because the WES 16-kip device and the Road Rater both apply a static load to the pavement, higher modulus values may be expected for granular materials. The allowable aircraft loads from the AIRPAVE program are shown in Figure 8. This evaluation considered the limiting strain in both the asphalt layer and the subgrade. All devices with the exception of the 15-kip WES FWD and the 24-kip Dynatest FWD indicated that the area could support a fully loaded B-52. When only the subgrade strain was

TABLE 3 Moduli Predicted from Deflection Basins from Different NDT Equipment

		Layer 1			Layer 2			Layer 3		
Test Area	Nondestructive Test Device	Thickness (in.)	Material	Elastic Modulus (psi)	Thickness (in.)	Material	Elastic Modulus (psi)	Thickness (in.)	Material	Elastic Modulus (psi)
2	WES 16-kip	10.0	AC	680,279	15.0	Limerock-stabilized base	59,740	Subgrade	Sand	37,209
	WES FWD			572,022			40,116			37,438
	Dynatest FWD			538,205			36,649			29,799
	Shell FWD			559,951			65,255			31,818
	Road Rater			452,499			90,633			50,928
	Dynaflect			154,052			403,405			22,579
3	WES 16-kip	5.5	AC	691,229	15.0	Limerock-stabilized base	40,926	Subgrade	Sand	26,573
	WES FWD			185,244			16,241			31,738
	Dynatest FWD			185,952			20,682			20,375
	Shell FWD			332,768			18,244			27,155
	Road Rater			537,513			35,074			24,344
	Dynaflect			52,175			40,381			23,872
4	WES 16-kip	7.0	AC	1,440,817	6.0	PCC	3,227,078	Subgrade	Sand	25,157
	WES FWD			1,982,381			2,047,265			23,242
	Dynatest FWD			1,903,426			1,841,818			22,108
	Shell FWD			2,334,218			1,387,285			17,160
	Road Rater			6,878,414			248,228			23,376
	Dynaflect			12,030,469			716,925			10,687

TABLE 4 Allowable Loads for the B-52 Determined Using AIRPAVE and the Standard Air Force Evaluation Procedure

					Allowable Load (kips)		
					AIRPAVE		
Test Area	Test Device	Design Aircraft	Design Pass Level	Design Load	Subgrade Criteria	Both Criteria	Standard Evaluation
2	WES 16-kip	B-52	15,000	490	490+	490+	490+
	WES FWD				490+	446	
	Dynatest FWD				490+	414	
	Shell FWD				490+	490+	
	Road Rater				490+	490+	
	Dynaflect				490+	490+	
3	WES 16-kip	B52	15,000	490	370	370	400
	WES FWD				421	211	
	Dynatest FWD				269	234	
	Shell FWD				358	223	
	Road Rater				334	334	
	Dynaflect				335	335	
4	WES 16-kip	B-52	15,000	490	490+	490+	333
	WES FWD				490+	490+	
	Dynatest FWD				490+	490+	
	Shell FWD				490+	490+	
	Road Rater				490+	490+	
	Dynaflect				351	351	

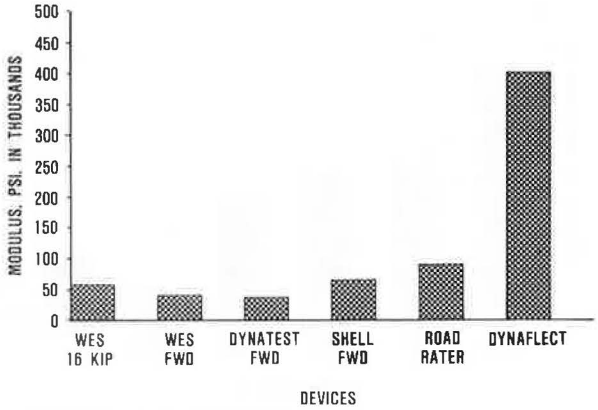

FIGURE 6 Comparison of the modulus values computed for the base course of Test Area 2.

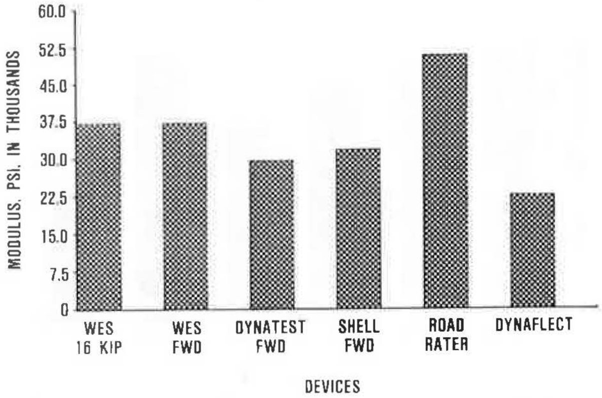

FIGURE 7 Comparison of the modulus values computed for the subgrade of Test Area 2.

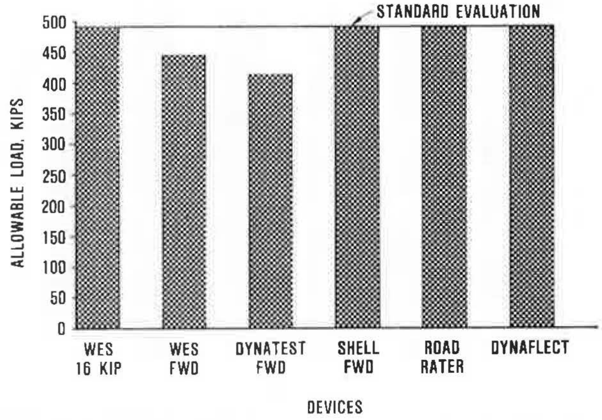

FIGURE 8 Allowable aircraft loads from AIRPAVE for Test Area 2.

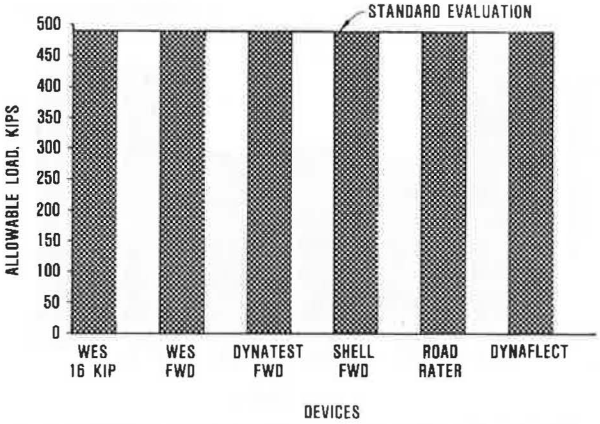

FIGURE 9 Allowable aircraft loads from AIRPAVE for Test Area 2 with only the subgrade strain criteria considered.

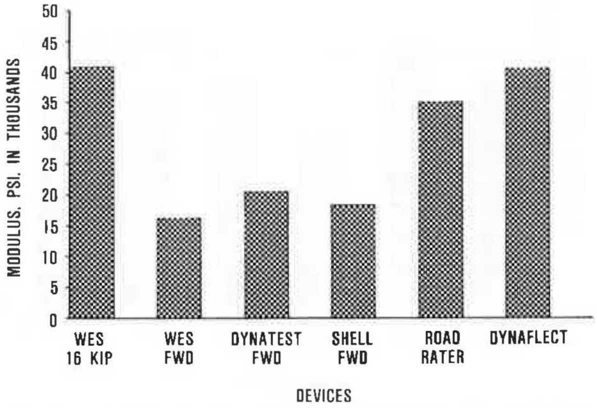

FIGURE 10 Comparison of the modulus values computed for the base course of Test Area 3.

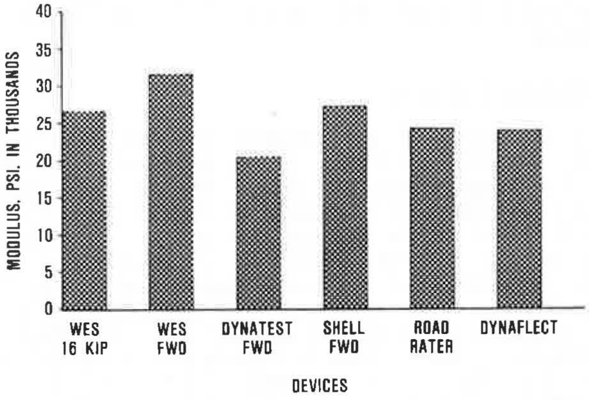

FIGURE 11 Comparison of the modulus values computed for the subgrade of Test Area 3.

considered, all devices yielded the maximum allowable load (490 kips as shown in Figure 9). This agrees with the standard evaluation that is based on the CBR design procedure and does not account for strain in the surface layer.

Analysis of Area 3

Modulus values for the base and the subgrade of Area 3 are shown in Figures 10 and 11. For the base course modulus, the values of the vibratory devices--the WES 16-kip, the Road Rater, and the Dynaflect--are higher than those of the FWDs. The values for the subgrade are similar.

The allowable aircraft loads using both asphalt and subgrade strain criteria are lower than the standard evaluation (Figure 12). When only the subgrade strain criteria are used, the allowable loads are near the standard evaluation (Figure 13). The differences in allowable load between the FWDs and the vibratory devices may be due to the lower base

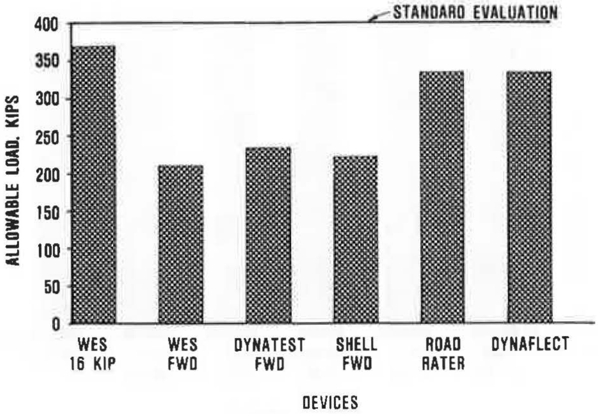

FIGURE 12 Allowable aircraft loads from AIRPAVE for Test Area 3.

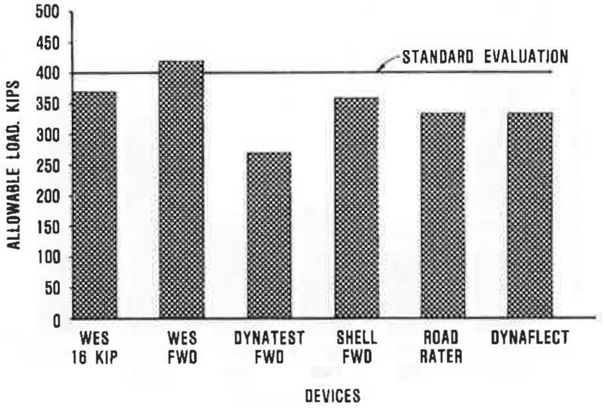

FIGURE 13 Allowable aircraft loads from AIRPAVE for Test Area 3 with only the subgrade strain criteria considered.

course modulus obtained from the FWD deflections, particularly when both strain criteria are considered.

Analysis of Area 4

A large variation was obtained for the base (PCC) layer for Area 4 (Figure 14). Some variation is seen in the subgrade modulus values (Figure 15). Evaluation of composite pavements is difficult when the thickness of the AC overlay is near the thickness of the PCC. A failure criterion (flexible or rigid) must be selected in a layered system evaluation. The flexible pavement criterion was selected for this area because the standard evaluation is for flexible pavement. Allowable aircraft loads are shown in Figure 16. The evaluation using Dynaflect data is nearer the standard evaluation than is the evaluation using all other devices. This may be discredited because the layer modulus values do not appear reasonable for the PCC and the sand subgrade.

CONCLUSIONS

An evaluation procedure based on layered elastic analysis was presented, and comparisons were made using deflection data from six different NDT devices on three pavement sections. The NDT testing data were taken from a study in which leaders in the field of NDT airfield evaluation were asked to evaluate pavements. These firms were allowed to test at any location within specified test areas; therefore, it was difficult to find test locations that were common to all devices. The following conclusions are presented:

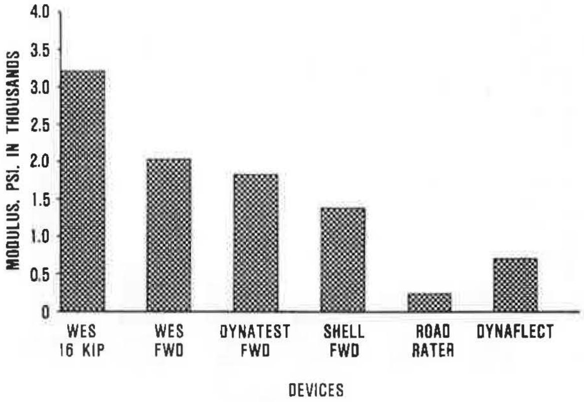

FIGURE 14 Comparison of the modulus values computed for the base course (PCC) of Test Area 4.

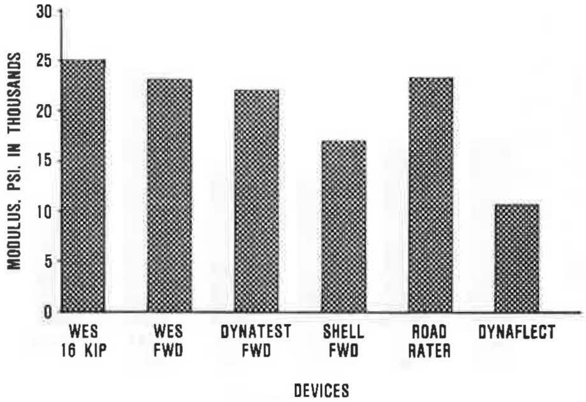

FIGURE 15 Comparison of the modulus values computed for the subgrade of Test Area 4.

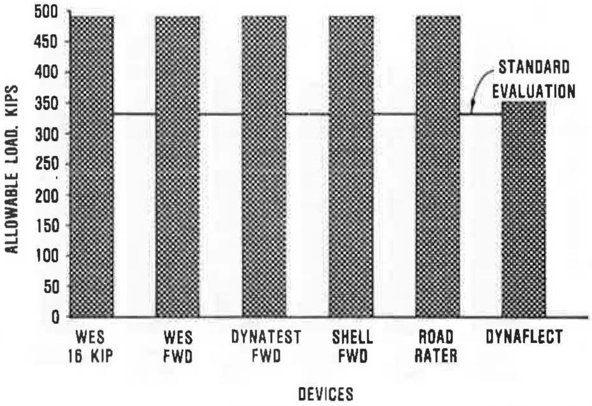

FIGURE 16 Allowable aircraft loads from AIRPAVE for Test Area 4.

1. Results from each device compare favorably with the standard evaluation procedure in terms of allowable gross aircraft loads.
2. The computed moduli of the base course materials are higher when a preload is applied as in the case of the WES 16-kip vibrator.

3. A study would be more beneficial in determining the differences in NDT equipment if it were conducted on a site where tests with all devices were conducted at the same test locations.

4. The allowable gross aircraft load for two of the three pavements evaluated was at the maximum for the B-52 aircraft, which is one of the most critical aircraft in terms of pavement evaluation. If further research is conducted, it is recommended that a site with fine grained subgrades, where design loads are less than maximum for the evaluated aircraft, be selected.

ACKNOWLEDGMENT

This paper was based on an Air Force Engineering and Services Center (AFESC) research project conducted by the U.S. Army Engineer Waterways Experiment Station (USAEWES). The authors gratefully acknowledge the support of the engineers at AFESC and USAEWES who were actively involved in this work.

The views expressed in this paper are those of the authors who are responsible for the facts and accuracy of the data. The contents do not necessarily reflect the official views or policies of the AFESC or USAEWES. This paper does not constitute a standard, specification, or regulation. The use of the following trade or manufacturing names was considered essential because they appear in the Air Force report on which this paper is based: Dynatest FWD, Shell FWD, Road Rater, and Dynaflect. Mention of the products listed does not constitute USAEWES endorsement or rejection of the products.

Discussion

Waheed Uddin, Phil Smith, and Harvey J. Treybig*

The authors are to be congratulated for carrying out this study on a large scale as reported by Hall (6). Direct comparison of different nondestructive devices by testing at the same locations on in-service pavement is undoubtedly an appropriate approach for a comparative study of these devices along with their respective evaluation methodologies. The Air Force report (6), from which the authors have extracted contents for their paper, is based on two objectives: (a) comparison of NDT devices and results from different evaluation procedures and (b) comparison of allowable load rating and overlay thickness predictions from these procedures with the standard test pit rating. However, the paper focuses only on some selected data from this large report. Unfortunately, the presentation of the data and results in this paper are out of context. A reader who has not reviewed the report (6) may misinterpret the results presented in the paper and form a biased opinion about the results.

Unfortunately, the results in the paper are not those that compare the results of a particular device and its analysis methodology. Instead data are taken from several devices and a single analysis package is misapplied. The discussion presented here centers around the following key points:

1. The results reported by each of the participants in the overall study (6) were available to the authors of the paper but were not reported in the paper; thus the major thrust of the overall study was omitted.

2. The authors used the participants' field measured deflection data as inputs to their own analysis and evaluation methodology. This is not the best systematic technique for comparing devices because it ignores proven methodology developed by each participant on the basis of the participant's NDT device.

3. The Dynaflect load and sensor configuration was improperly modeled by the authors, which results in inaccurate deflection basins and moduli predictions.

COMPARISON OF DYNAMIC DEFLECTION BASINS

There is no explanation in the paper of why results from only three of the five test areas are reported. Only one basin measured by each NDT device on each of Areas 2, 3, and 4 is used for pavement evaluation; the full report is much broader in scope.

The deflection basins given in Table 2 and shown in Figures 3-5 do not properly represent the Dynaflect loading and geophone configuration. A more rational approach to comparing deflection basins from different NDT devices suggests a plotting of normalized deflections versus radial distances of sensors from the center of the test load (8) as shown in Figure 17. The radial distances of the

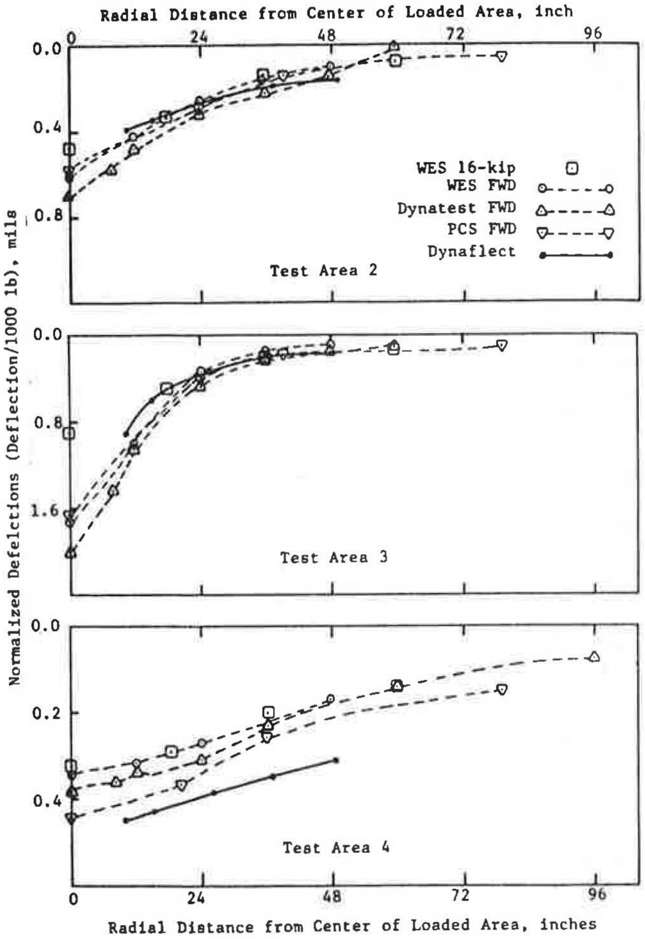

FIGURE 17 Normalized deflection basin plots for different NDT devices.

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*ARE, Inc., 2600 Dellana Lane, Austin, Tex. 78746

TABLE 5 Summary of Estimated Young's Moduli Based on Evaluation Methodologies of Participants

Test Area	NDT Device	Moduli Reported by Participants *(6)* in psi			Percentage Difference in Modulus from BISDEF and Participants {100 x [Modulus (BISDEF) – Modulus (participant)] ÷ Modulus (participant)}		
		Surface	Base	Subgrade	Surface	Base	Subgrade
2	WES 16-kip	250,000	51,000	39,000	+172.1	+17.1	–4.6
	WES FWD	250,000	36,000	39,000	+128.8	+11.4	–4.0
	Dynatest FWD	348,000	32,000	26,000	+54.6	+14.5	+14.6
	PCS FWD	635,000	35,300	51,200	–11.8	+84.8	–37.8
	Berger Profiler	400,000	100,000	37,000	+13.1	–9.4	+37.6
	Dynaflect	500,000	120,000 (60,000)[a]	34,500	–69.2	+236.2	–34.5
3	WES 16-kip	250,000	44,000	24,000	+176.5	–7.0	+10.7
	WES FWD	250,000	13,500	24,000	+176.5	+20.3	+32.2
	Dynatest FWD	401,000	16,000	20,000	–53.6	+29.3	+1.9
	PCS FWD	635,000	10,000	41,000	–47.6	+82.4	–33.8
	Berger Profiler	300,000	50,000	24,000	+79.2	–29.9	+1.4
	Dynaflect	200,000	60,000 (35,000)[a]	27,000	–73.9	–32.7	–11.6
4[b]	WES 16-kip	250,000	500,000	19,000	+476.3	+545.4	+32.4
	WES FWD	250,000	500,000	18,000	+693.0	+309.4	+29.1
	Dynatest FWD	533,000	4,500,000	26,200	+257.1	–59.1	–15.6
	PCS FWD	635,000	900,000	30,600	+267.6	+54.1	–43.9
	Berger Profiler	800,000	4,000,000	24,000	+759.8	–93.8	–2.6
	Dynaflect	300,000	6,000,000	21,000	+3910.2	–88.1	–49.1

[a] Subbase modulus.
[b] Base in Text Area 4 is a PCC layer.

Dynaflect sensors are 10.0, 15.6, 26.0, 37.4, and 49.0 in. from the center of the loaded area under each loading wheel. It can be seen from the normalized plots (Figure 17) that (a) the pavement response is affected by the loading mode and (b) the response is device dependent, as is apparent from variations in the data of the three FWD units.

EVALUATION OF PAVEMENT MODULI

The authors have not chosen in this paper to report results of the pavement evaluations made independently by the participants. Each participant has used an evaluation methodology to analyze data from its respective NDT device. The paper inaccurately implies that the Dynaflect does a poor job; the full report shows excellent correlation of the Dynaflect results, based on the participant's analysis and evaluation.

Pavement Evaluation by Participants

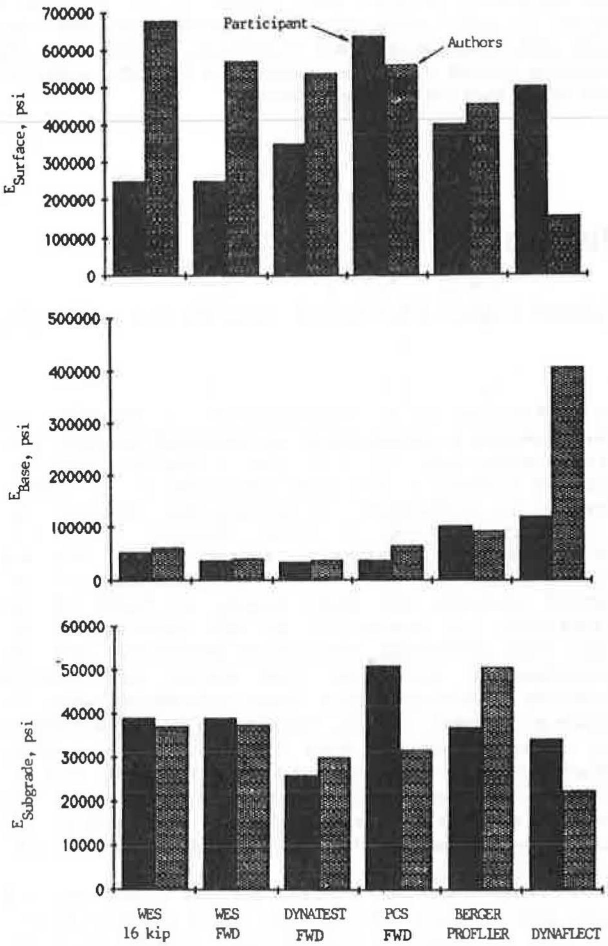
Table 5 gives the results extracted from the full report (6), as well as a comparison with the moduli reported by the authors.

The moduli from WES 16-kip and WES FWD devices are in most cases identical, although considerable differences exist in the normalized deflection basins from the two devices.

It is to be appreciated that the results from the methodologies of the participants are in general similar and within a reasonable margin of error (Figures 18-20).

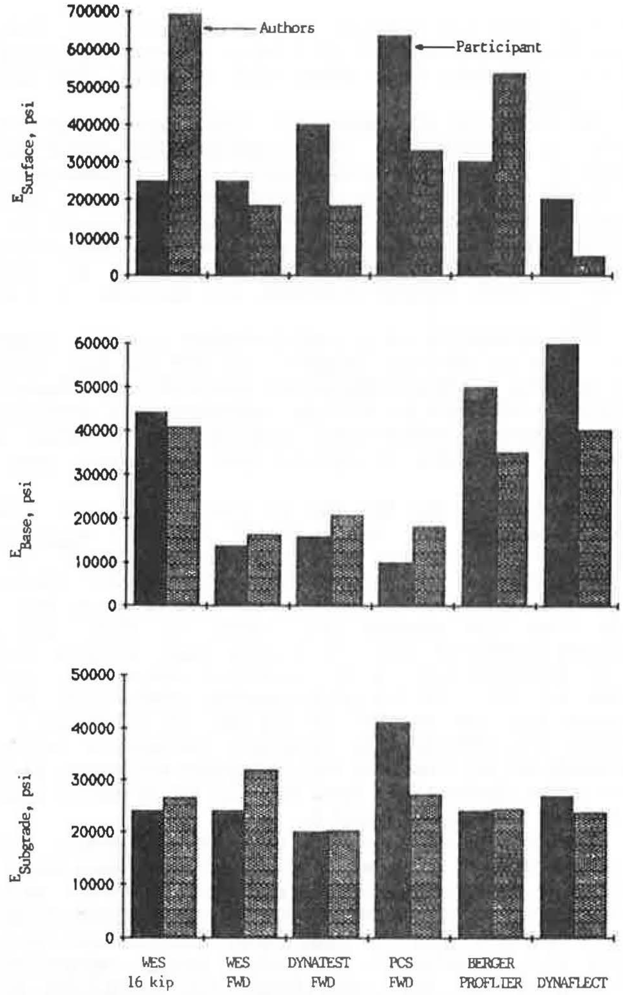
BISDEF Methodology

The authors provide only a cursory description of their BISDEF program. Its parent program, CHEVDEF, was specifically designed for Road Rater model 2008 (1). Ample explanation of the following points is needed.



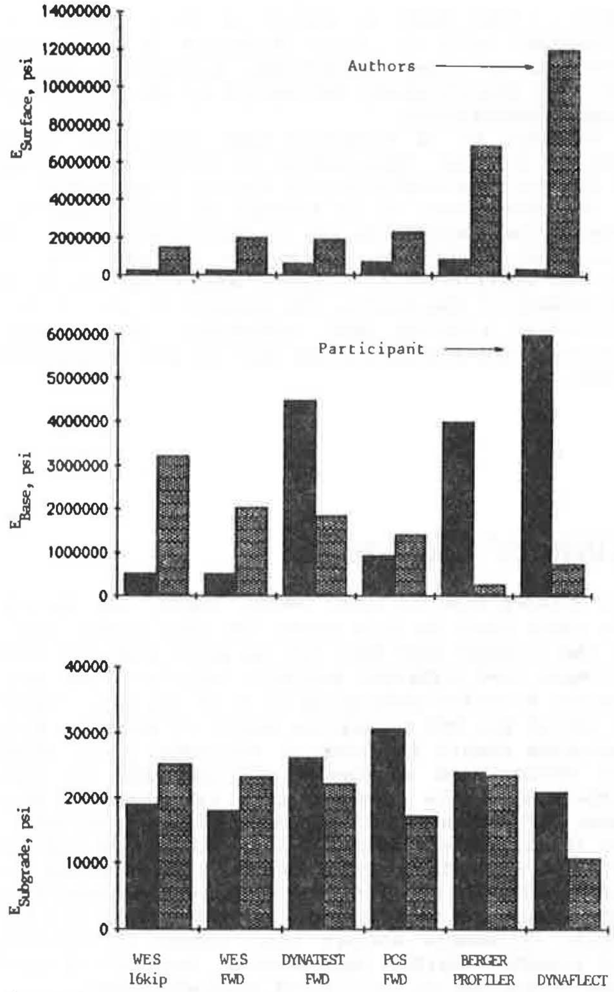
(Black indicates the results reported by an individual participant. Grey shows the results of the authors.)

FIGURE 18 Comparison of pavement evaluation results for Test Area 2.



(Black indicates the results reported by an individual participant. Grey shows the results of the authors.)

FIGURE 19 Comparison of pavement evaluation results for Test Area 3.



(Black indicates the results reported by an individual participant. Grey shows the results of the authors.)

FIGURE 20 Comparison of pavement evaluation results for Test Area 4.

1. Assumptions used in applying BISDEF to NDT data.
2. Using an arbitrary value of 20 ft for the depth to an assumed rock layer is a debatable point. Bush (1) found 20 ft to be a good assumption for obtaining a better fit for measured Road Rater 2008 deflections at the Pennsylvania test road facility. The authors apply the 20 ft assumption to all other NDT devices and geological conditions and to rigid pavements.
3. The basin-fitting technique in BISDEF is a function of an initial input estimate of moduli and a reasonable range defined by maximum and minimum values (E_{max} and E_{min}). A table that gives these values should have been provided by the authors.

Test Area 4

This is a composite pavement site. Independent evaluations from the participants (Table 5 and Figure 20) show moduli of all layers in reasonable agreement. In contrast, BISDEF produces unreasonably high values of AC modulus for all NDT devices. These high values are practically not possible in the climatic conditions of Florida. It would be interesting to know the E_{max} value of AC layer used in the analysis. Evidently this value must be more than 12 million psi.

On the basis of the BISDEF results, the authors discredit the Dynaflect for unreasonable values of PCC layer (716,925 psi) and subgrade (10,687 psi). The authors do not comment on the 12 million psi value for AC modulus. However, the in situ moduli (Table 5 and Figures 18-20) and allowable aircraft loads, evaluated by the discussants and presented in detail in the report (6), clearly demonstrate that the discussants' methodology does an excellent job: the results for allowable loads and overlay thickness are consistently reasonable.

COMMENTS ON AUTHORS' CONCLUSIONS

For the benefit of readers who do not have access to the report (6), the moduli evaluated by each participant should have been reported in this paper.

It is inferred in the second conclusion that a preload will result in a higher base modulus. This is apparently in error. The BISDEF program has computed a high base modulus (65,255 psi) for PCS FWD with no preload, which is not significantly different from the base modulus (59,740 psi) for the WES 16-kip device.

Conclusion 3 is quite true and timely, but there should be some independent measurement of in situ dynamic moduli (e.g., using different wave propagation techniques). Comparison with results of static tests or laboratory M_R values is always debatable. Laboratory tests can never duplicate in situ environmental or stress conditions. Laboratory results are also significantly influenced by the effects of sample disturbances.

Finally, it is suggested that this paper could then be retitled "Application of BISDEF Methodology to NDT Data for Evaluation of Airport Pavements."

The main lesson to be learned is that compatible comparisons involve the use of the procedure and the analytical techniques appropriate to each device, not the application of a common analytical technique regardless of the device. The concept of system compatibility requires that compatible measurements, analyses, and predictions be used in any engineering study.

Authors' Closure

The authors wish to thank Uddin, Smith, and Treybig for their input to this paper. The discussants point to the results from Hall (6) in which each NDT participant used different analysis techniques for each device. A stated conclusion of Hall (6) was, "Based on use of the NDT evaluation method at MacDill, wide variation occurs in terms of allowable loads among the results and substantial disagreement of some methods with the standard test set method." This paper was presented to illustrate that the variability in allowable load could be significantly reduced by using a single analysis technique. This would allow an airport owner to use different equipment or consultants and be reasonably confident that the end result (allowable airport load, passes to failure, and possible overlay requirements) would be consistent regardless of the type of equipment used.

It was demonstrated, contrary to what the discussants say, that a single analysis technique can be used with different devices to produce consistent results.

The authors agree that a footnote should be added to Tables 1 and 2 to indicate that for the Dynaflect device the distance from the center of the load area is the distance from the midpoint of the loading wheels. The Dynaflect device was correctly modeled in the BISDEF program using two loaded areas and a deflection measurement centered between the loaded areas and four other deflections spaced at 1-ft intervals away from the first sensor.

Two methods can be used to compare deflection basins. One method, illustrated in the paper, shows differences in magnitude. The method used by the discussants is also acceptable. The selection depends on the point to be made. In the case of this paper, the authors were illustrating the relative magnitudes as shown.

In the prediction of moduli, the method presented by the authors produces the best fit of measured deflections to those determined from the layered theory. The moduli values reported in this paper are given in Table 10 of Hall (6). The differences given by the discussants in Table 5 and shown in Figures 18-20 are from values used for evaluation by each participant. The values that the discussants report were determined from a large number of tests over the entire pavement area and not from points where tests were conducted with all devices. Those values were also adjusted for design environmental conditions and were not the actual values that were determined from field data. For example, the modulus of the asphalt surface layer was adjusted to represent a value for a design pavement temperature. Moduli values reported in this paper are as determined from field data at a given test location with all NDT devices.

As stated in the paper, the BISDEF program is the same as CHEVDEF with the exception that BISAR was used as the multilayered elastic routine instead of CHEVRON. The advantages to using BISAR are that multiple loads can be evaluated, as in the case of the Dynaflect, and different layer interface conditions can be considered. The assumptions, which are the same for most layered programs, are the same in both cases.

The assumption of a semi-infinite subgrade layer can also be debated. Research at WES on test sections with surface deflections measured by different means in addition to NDT has indicated that measured and computed deflections compare better when a boundary condition is applied such as a rigid layer at 20 ft.

Research at the WES and as reported by Bush (1) indicates that the magnitude or range of E_{max} or E_{min} has little effect on the predicted moduli.

Discussants' questions about the moduli values from the Dynaflect deflections on Site 4 again deviate from the purpose and intent of this paper. Values presented are the values that produce the best possible fit to the measured deflections and were not adjusted to environmental conditions. The reason for the unusual values may be explained by Figure 17. Whereas the Dynaflect deflection basin, normalized for load, is significantly different from the other devices for Test Area 4, it is quite similar for Test Areas 2 and 3.

The conclusion that the base course moduli are greater when a preload is applied was questioned. This was true eight times out of nine when the FWDs were compared to the WES 16-kip vibrator (also eight of nine times when the Road Rater and the Dynaflect were each compared to the FWDs). Other comparative studies at the WES have shown this condition to occur in nearly all cases.

The authors believe that a single approach must be developed for each major airport authority such as the FAA, Air Force, Army, Navy, or state to ensure that reasonable comparisons of structural capacity can be obtained from different evaluations. The MacDill study concluded that variation could be expected from different procedures. The variation is due in part to the different models and different failure criteria that are used.

The development of pavement NDT equipment during the last 10 years has provided excellent tools for determining in situ material properties under simulated design loading conditions. Understanding the results from different devices can improve the overall assessment of pavement capacities and life.

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Application of Simplified Layered Systems to NDT Pavement Evaluation

GDALYAH WISEMAN, JACOB GREENSTEIN, and JACOB UZAN

ABSTRACT

Presented are nondestructive testing (NDT) deflection measurements on flexible, rigid, and composite pavements obtained with two vibratory devices, the Pavement Profiler and the WES 16-kip vibrator, and one impulse loading device, the falling weight deflectometer (FWD). The deflection bowls are analyzed in terms of the elastic parameters of layers using the Hogg, the Burmister, and the Odemark-Ullidtz approximation to linear layered elastic system models. The results are compared with those obtained using more exact solutions and are found to be satisfactory. The evaluated elastic parameters were found to be similar for all three NDT devices for the subgrade and the surface layers of the pavement. Lower elastic moduli were found for the base course with deflection bowls produced by the FWD than for those produced by the other two vibratory devices. Most pavement evaluation is done on pavements that have been in service for many years and have a varied history of maintenance and overlaying. The resulting lack of homogeneity must be considered in developing a strategy for meaningful pavement evaluation. It is therefore necessary to examine a large number of test points. The use of simplified layered system models for NDT pavement evaluation is, therefore, recommended. This makes it economically feasible to analyze each test point with respect to the relative contribution of the strength of the subgrade and the condition of the pavement structure to the overall performance of the pavement. It is also possible to examine material variability for each of the layers. Results of such computations given in this paper show higher variability in the asphaltic concrete and the base course layers than in the concrete or the subgrade.

Pavement evaluation is most frequently done on pavements that have been in service for many years and have a varied history of maintenance and overlaying. The resulting lack of homogeneity must be considered in developing a strategy for meaningful pavement evaluation. A large number of test points are therefore mandatory, so that the responsible engineer can make intelligent decisions with due regard to the statistical nature of the problems of pavement evaluation and rehabilitation.

Nondestructive testing (NDT) and deflection measurements are now universally recognized methods for the structural evaluation of road and airfield pavements. In many cases use is still made of empirical correlations between deflection under a test load and pavement performance. There is, however, general recognition that the maximum benefit is derived from NDT deflection measurements if the deflection bowl is interpreted in terms of the material parameters of the various component layers of pavement structure and subgrade.

The results of NDT deflection measurements on