

# Project-Level Structural Evaluation of Pavements Based on Dynamic Deflections

WAHEED UDDIN, A. H. MEYER, W. R. HUDSON, and K. H. STOKOE II

## ABSTRACT

The framework of a structural evaluation system for pavements, which is based on the mechanistic evaluation of dynamic deflection data, is described. The computer program RPEDDL has been developed for the evaluation of dynamic deflection basins measured on rigid pavements by nondestructive testing devices (a falling weight deflectometer and a Dynaflect). The analysis models presented in this paper include (a) a self-iterative procedure to determine in situ moduli of pavement layers, assuming a layered linearly elastic medium; (b) a self-iterative procedure for determining nonlinear strain-dependent moduli of granular layers and subgrade; and (c) a procedure for predicting fatigue life and existing structural capacity. A methodology has been developed to eliminate any need for assuming initial values of moduli. This has also improved efficiency of the self-iterative basin matching procedure and ensured unique values of the in situ moduli. Implementation of the proposed computerized evaluation procedures also provides a rational way to delineate sections for rehabilitation design.

Nondestructive testing (NDT) for structural evaluation of pavements is an important part of selecting rehabilitation and reconstruction strategies in the project-level pavement management process. The development of mechanistic overlay design procedures (1-3) has placed more emphasis on obtaining in situ material properties by analyzing deflection data. The realization that pavement response is affected by applied stress level, rate, and mode of loading and demand for faster and easier test methods have led to the development of several other types of NDT devices, such as the road rater and the falling weight deflectometer (FWD). The widespread use of applying a mechanistic approach to structural evaluation of pavement has resulted in (a) the measurement of deflection basins by recording dynamic deflections at more than one point during the test, and (b) the application of multilayered linear-elastic theory for analyzing the measured basin to derive in situ Young's moduli, assuming a pavement model as shown in Figure 1.

In this paper investigations performed for developing a computerized structural evaluation system based on dynamic deflection basins are described. A computer program [RPEDDL (a rigid pavement structural evaluation system based on dynamic deflections--version 1.0)] has been developed and is described in this paper.

## NDT DEVICES AND DYNAMIC DEFLECTION BASIN MEASUREMENT

Only the Dynaflect and the FWD are considered in this study. Standard configurations of load and deflection sensors (geophones) for the Dynaflect are assumed. Detailed descriptions of the Dynaflect and the test procedure are given elsewhere (4,5). The Dynaflect applies a sinusoidal vibrating load of a 1,000-lb peak-to-peak amplitude through two steel wheels that are 20 in. apart. Peak-to-peak surface deflections are measured by five geophones spaced 12 in. apart, with the first geophone located midway between the loading wheels. The radial distances of

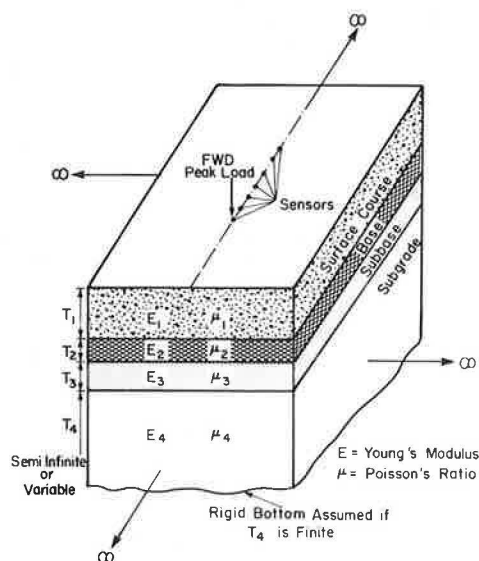


FIGURE 1 Multilayer linearly elastic model of pavement.

the geophones from each loading wheel are 10.00, 15.62, 26.00, 37.36, and 49.03 in. Basically, the FWD applies an impulse load by dropping a known mass from a predetermined height on a loading plate, which is assumed to be 11.8 in. in diameter in this study. An array of seven geophones is assumed in this research. The sensor at the center of the loading plate measures maximum deflection. Other geophones are assumed to be 12 in. apart, with radial distances at 0.0, 12.0, 24.0, 36.0, 48.0, 60.0, and 72.0 in.

FWD results are presented graphically as a deflection basin in this paper, plotted with radial distances as abscissas and normalized deflections as ordinates. FWD deflections are normalized with re-

spect to a 1,000-lb force to remove the influence of test load variations on deflections.

#### NDT EVALUATION OF IN SITU MODULI

An NDT device positioned far from the pavement edge and midway between two transverse joints or cracks can be used for the purpose of in situ material characterization and structural evaluation. Uddin et al. (6) have reported that Dynaflect deflection basins measured this way on continuously reinforced-concrete (CRC) pavements were practically free of temperature effects. A review of existing practices for the evaluation of deflection data and formulation of the self-iterative model developed in this study is presented in the following sections.

#### Review of NDT Evaluation Procedures

A detailed review of the published research on back-calculating moduli of two- or three-layer pavements using deflection basin parameters and layered theory is presented by Uddin et al. (7). A summary of deflection basin parameters is presented in Table 1. Finite element models have also been used by some researchers (8). These methods were generally developed by assuming fixed values of some parameters. Basin parameters do not use all the information that can be extracted from the use of the complete deflection basin. Another limitation is that each procedure has been developed for a specific NDT device and for some specific ranges of moduli. Generally, a bottom layer is assumed to be semi-infinite, which can result in considerable overestimation of error in the subgrade modulus if a rock layer exists within 20 ft (9). These considerations are often overlooked when a user applies these procedures in practice.

Inverse application of layered theory by fitting a measured deflection basin with a predicted deflection basin using an iterative procedure is the most promising method for calculating in situ moduli. In the past few years a number of self-iterative computer programs have been developed that use this approach, as summarized in Table 2. Some of the major features of these self-iterative procedures are as follows:

1. Generally these procedures are designed to handle only flexible pavements.

2. Semi-infinite subgrade is assumed in nearly all procedures. Effects of the existence of a rigid layer at a finite depth of subgrade on computed deflections and derived moduli are not addressed in the development of these methods.

3. Corrections to the derived moduli for non-linear behavior of granular layers and subgrade are not considered in these procedures, with the exception of OAF and ISSEM4.

4. All these procedures are user dependent as far as the influence of initially assumed moduli on the convergence process and final moduli is concerned.

5. Dynamic aspects of the dynamic deflection data and effect of loading mode are ignored in all these procedures.

Research related to the self-iterative procedure developed in this study is presented in the following section.

#### Parameters Affecting Deflection Basin

To be precise, NDT data should be evaluated by using a dynamic analysis model. Dynamic loading on a pavement surface causes disturbances in the pavement subgrade system. If the pavement subgrade system is assumed to be linearly elastic, then a true dynamic analysis is possible by the application of the theory of stress wave propagation in layered elastic media. This theory is already being applied in the evaluation of dynamic moduli and layering in a pavement by the spectral analysis of surface waves (4). At the present state of knowledge, the layered linearly elastic theory can be used for mechanistic interpretation of dynamic deflection basins for all practical purposes. Therefore, the ELYSM5 computer program was selected for structural response analysis in this study.

#### Young's Moduli

A parametric study to investigate the sensitivity of theoretical deflection basins to the rate of change of moduli for a rigid pavement was performed in earlier research work (4). In that study one of the E values was varied by  $\pm 100$  percent whereas the other E's were fixed at their original levels. Thicknesses and Poisson's ratios were fixed at constant values. An interesting conclusion was that a

TABLE 1 Summary of Deflection Basin Parameters (7)

Parameter	Definition <sup>a</sup>	NDT Device <sup>b</sup>
Dynaflect maximum deflection (DMD)	DMD = $d_1$	Dynaflect
Surface curvature index (SCI)	SCI = $d_1 - d_2$	Dynaflect, road rater model 400
Base curvature index (BCI)	BCI = $d_4 - d_5$	Dynaflect
Spreadability (SP)	$SP = \left( \sum_{i=1}^5 d_i / 5d_1 \right) \times 100$	Dynaflect
	$SP = \left( \sum_{i=1}^5 d_i / 4d_1 \right) \times 100$	Road rater model 2008
Basin slope (SLOP)	SLOP = $d_1 - d_5$	Dynaflect
Sensor 5 deflection ( $W_5$ )	$W_5 = d_5$	Dynaflect
Radius of curvature (R)	$R = r^2 / \{ 2d_m [(d_m/d_r) - 1] \}$	Benkelman beam
Deflection ratio ( $Q_r$ )	$Q_r = r/d_o$	FWD, Benkelman beam
Area, in inches (A)	$A = 6 \{ 1 + 2(d_2/d_1) + 2(d_3/d_1) + (d_4/d_1) \}$	Road rater model 2008
Shape factors ( $F_1, F_2$ )	$F_1 = (d_1 - d_3)/d_2$ $F_2 = (d_2 - d_4)/d_3$	Road rater model 2008
Tangent slope (TS)	TS = $(d_m - d_x)/x$	—

<sup>a</sup>d = deflection; subscripts 1, 2, 3, 4, 5 = sensor locations; o = center of load; r = radial distance; m = maximum deflection; x = distance of tangent point from the point of maximum deflection.

<sup>b</sup>The NDT device for which the deflection parameter was originally defined.

TABLE 2 Summary of Self-Iterative Procedures for Evaluation of Pavement Modulus from Deflection Basins (7)

Procedure Title	Source	Pavement Model (n = no. of layers)	Layered Theory Program for Analysis	NDT Method	Input	Output
* <sup>a</sup>	Anari and Wang, 1979; Pennsylvania State University	Four layers, flexible	BISAR	Road rater 400	$d_i$ $i = 1$ to 4	$E_1, E_2, E_3, E_4$
ISSEM4	Sharma and Stubstad, 1980; Dynatest	Four layers, flexible	ELSYM5	FWD	$d_i$ $i =$ variable	$E_1$ to $E_4$ for four layer input
CHEVDEF <sup>b</sup>	Bush, 1980; U.S. Army Corps of Engineers Waterways Experiment Station	Four layers (not to exceed number of deflections)	CHEVRON	Road rater 2008	$d_j$ $i = 1$ to maximum 4 ( $i = 1 + n$ )	$E_j$ $j = 1$ to $n$
OAF <sup>c</sup>	FHWA, 1981; Resource International	Three or four layers, flexible	ELSYM5	Dynalect, road rater, or FWD	$d_i$ $i =$ variable	$E_j$ $j = 1$ to 3 or $j = 1$ to 4 (overlay thickness)
INVERSE	Hou, 1977; University of Utah	$n = *$	CHEV5L	*	$d_i$ $i =$ variable	$E_j$ $j = 1$ to $n$
*	Tenison, 1983	Three layers, flexible	Chevron's N LAYER	Road rater 2000	$d_i$ $i = 1$ to 4	$E_j$ $j = 1$ to 3
RPEDD1 <sup>d</sup>	Uddin et al., 1984; University of Texas	Three or four layers, rigid	ELSYM5	Dynalect, FWD	$d_i$ $i = 1$ to 5 or $i = 1$ to 7	$E_j$ $j = 1$ to 3 or 4 (remaining life)
FPEDD1 <sup>d</sup>	Uddin et al., 1984; University of Texas	Three or four layers, flexible	ELSYM5	Dynalect, FWD	$d_i$ $i = 1$ to 5 or $i = 1$ to 7	$E_j$ $j = 1$ to 3 or 4 (remaining life)

Note: \* = not known or available.

<sup>a</sup>Thickness, Poisson's ratio, initial seed modulus of each layer (except the thickness of bottom layer) are required input. Allowable ranges of moduli are also required.

<sup>b</sup> $d_i$  = deflection reading measured at  $i$ th sensor.

<sup>c</sup>Can be easily modified to handle other NDT devices.

<sup>d</sup>Another program, OAR, has also been developed recently by the same researchers (for rigid pavement overlay design).

<sup>e</sup>These procedures are developed in the present study (7).

deflection basin is least sensitive to a change in the moduli of intermediate layers and highly sensitive to even a small change in the subgrade modulus. It is inferred from this study that, to obtain a best fit, a change in the modulus of the  $i$ th layer ( $\Delta E_i$ ) can be predicted from the discrepancy ( $\Delta d_j$ ) between an original deflection and its present value that corresponds to the  $j$ th sensor. For a four-layer rigid pavement, the following conceptual relationships are formed for later use in the convergence process designed for the self-iterative model:

$$\Delta E_4 \approx f(\Delta d_j) \quad (1)$$

where  $d_j$  is the deflection at the 5th sensor of the Dynalect and the 6th or 7th sensor of FWD,

$$\Delta E_3 \approx f(\Delta d_k) \quad (2)$$

$$\Delta E_2 \approx f(\Delta d_1, \Delta d_k) \quad (3)$$

where  $d_k$  is the deflection at intermediate sensors located between the first and last sensors, and  $d_1$  is the deflection at the first sensor (maximum deflection), and

$$\Delta E_1 \approx f(\Delta d_1) \quad (4)$$

A cycle of iterations starts by predicting the approximate change in the subgrade modulus and then proceeds to the corrections of the moduli of upper layers. This is the basis of an algorithm developed for the convergence process.

#### Thickness Information

The other important input parameter that influences theoretical deflection response is thickness. Deflection basins were calculated by varying the original thickness of a layer by factors of 2 and 0.5 while keeping all other input data fixed at original

levels. This study indicates that, if design thicknesses are assumed for deflection basin analysis, slight variations in actual thicknesses of intermediate layers are not as critical as those of the surface concrete layer.

#### Development of a Self-Iterative Model

##### Assumptions

A set of simplified assumptions is necessary to validate the application of layered theory for determining in situ moduli from deflection basins. The assumptions can be separated into two groups:

1. Assumptions inherent in the use of layered linear-elastic theory to calculate pavement response. These are related to material properties, thickness information, boundary conditions, and so forth.

2. The second group of assumptions is required for NDT evaluation of a pavement in existing condition.

- \* The existing pavement is considered to be a layered elastic system (Figure 1). Therefore, the principle of superposition is valid for calculating response because of more than one load.

- \* The peak-to-peak dynamic force of the Dynalect is modeled as two pseudo-static loads of 500 lb each uniformly distributed on circular areas (each 3 in.<sup>2</sup>). The peak dynamic force of the FWD is assumed to be equal to a pseudo-static load uniformly distributed on a circular area represented by the FWD loading plate.

- \* Thickness of each layer is assumed to be known and exact.

- \* Subgrade is to be characterized by assigning an average value to its modulus of elasticity.

## Methodology

A methodology has been formulated to determine in situ moduli based on a best fit of measured deflection basin within reasonable tolerances. The methodology relies on the iterative use of a procedure of successive correction until a best fit of the measured basin is obtained.

To start with, deflections are calculated from the initial input values of moduli (referred to as seed moduli in this study). The first cycle of iterations is equal to the number of layers in the pavement. In each cycle the first iteration is made to correct the subgrade modulus. ELYSM5 is then called to calculate theoretical deflections. Correction is then applied to the modulus of the next upper layer and ELYSM5 is again called to calculate theoretical deflections. The procedure of successive correction is continued until moduli of all layers have been checked for correction. Then another cycle of iterations starts again from the subgrade layer. The relationship used in the procedure of successive correction is given in the generalized form

$$ENEW_i = E_i (1.0 - CORR_i \cdot ERRP_k \cdot 0.5) \quad (5)$$

where

$ENEW_i$  = corrected value of Young's modulus of  $i$ th layer,

$E_i$  = value of Young's modulus of  $i$ th layer in the previous iteration (for the first iteration it is seed modulus),

$CORR_i$  = correction factor for  $i$ th layer, and

$ERRP_k$  = discrepancy between measured deflection and predicted deflection (using  $E_i$  value) of  $k$ th sensor(s) as percentage error.

Only one-half of the discrepancy is meant to be removed in each iteration. Correction factors ( $CORR_i$ ) are based on the parametric study described earlier. Iterations are stopped when one of the following criteria is reached: (a) the maximum absolute discrepancy between calculated and measured deflections is equal to or less than the permissible tolerance, (b) any correction in a modulus value causes the discrepancies between calculated and measured deflec-

tions to increase, or (c) the allowable number of iterations is maximum.

## Description of BASINR

Subroutine BASINR is the self-iterative procedure to determine in situ moduli. The procedure can be used to analyze three- and four-layered pavements (as illustrated in Figure 2). The provision for a default procedure to obtain seed moduli from input data is an important part of BASINR and a significant improvement over other self-iterative procedures. Three types of tolerances allow ELYSM5 calculations to be skipped if the change in a modulus value is insignificant. The program is also designed to handle a rigid layer at some finite depth of subgrade.

## Uniqueness of NDT-Based In Situ Moduli

A severe limitation in any deflection basin fitting method is the nonuniqueness of derived moduli. In addition, a basin matching procedure is generally sensitive to initially assumed seed moduli, especially if these values are drastically different from actual moduli. The approach used in this study to obtain a unique set of in situ moduli is to use the default procedure for seed moduli. Predictive equations have been developed for the Dynaflect and the FWD. Numerous theoretical deflection basins were generated for combinations of pavements based on a fractional factorial design (Table 3). The theoretical basins were later used to develop nonlinear predictive equations for Young's modulus ( $E_i$ ) of each layer, with  $R^2$  values ranging from 0.7 to 0.99. The provision for default seed moduli eliminates guesswork in selecting seed moduli and ensures a unique result.

## Applications

The use of default seed moduli also results in fewer iterations for convergence. Generally, two to eight iterations are sufficient to reach a unique set of moduli. For validation of BASINR, theoretical deflection basins generated by ELYSM5 with preselected moduli were used to predict moduli. An example for the Dynaflect is shown in Figure 3 (7). Moduli calculated from a theoretical FWD deflection basin are shown in Figure 4 (7). In both examples zero values for seed moduli were entered in the inputs.

## NONLINEAR MODELING OF GRANULAR MATERIALS AND SUBGRADE

### Stress-Dependent Moduli

Characterization of the nonlinear behavior of granular materials and subgrades is normally based on

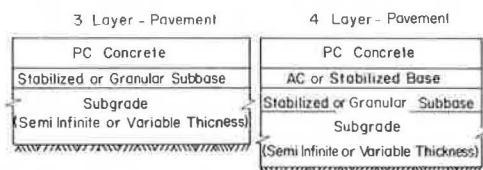
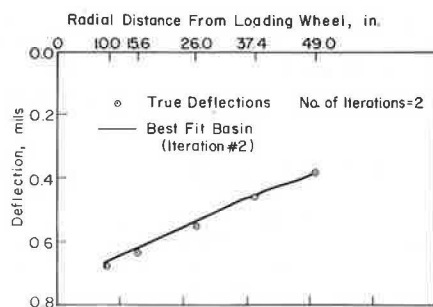


FIGURE 2 Typical rigid pavements analyzed by RPEDD1.

TABLE 3 Fractional Factorial Design to Generate Deflection Basin Data for Development of Moduli-Predictive Equations

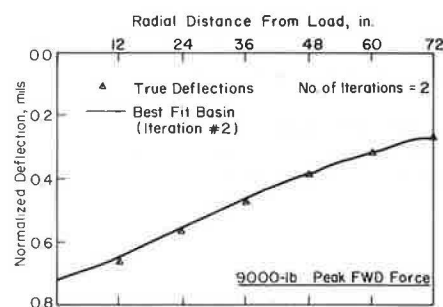
	Factors						
	$T_1$ (in.)	$T_2$ (in.)	$T_3$ (in.)	$E_4$ (psi)	$E_3$ (psi)	$E_2$ (psi)	$E_1$ (psi)
Levels							
Low	8	0	6	5,000	30,000	100,000	2,000,000
Medium	10	4	9	15,000	150,000	500,000	4,000,000
High	13	8	12	45,000	450,000	1,000,000	6,000,000
Semi-infinite subgrade in all cases	PCC thickness	Base thickness	Subbase thickness	$E_{\text{Subgrade}}$	$E_{\text{Subbase}}$	$E_{\text{Base}}$	$E_{\text{PCC}}$

Note: Full factorial =  $3^7$ ; 1/9th fractional factorial =  $3^5 = 243$  combinations; PCC = portland cement concrete.



Assumed Pavement	True	Young's Moduli (psi)		
		Input Seed	Default Seed	Predicted
8-in. P.C. Concrete	2,500,000	0	2,880,953	2,880,953
6-in. Cement-Treated Base	200,000	0	263,467	263,467
6-in. Granular Subbase	40,000	0	41,942	37,510
Semi-Infinite Subgrade	15,000	0	13,981	14,594

FIGURE 3 Young's moduli evaluated from a theoretical Dynaflect deflection basin (7).



Assumed Pavement	True	Young's Moduli (psi)		
		Input Seed	Default Seed	Predicted
8-in. P.C. Concrete	2,500,000	0	3,419,995	2,902,965
6-in. Cement-Treated Base	200,000	0	245,034	214,592
6-in. Granular Subbase	40,000	0	412,83	41,283
Semi-Infinite Subgrade	15,000	0	14,027	14,807

FIGURE 4 Young's moduli evaluated from a theoretical FWD deflection basin (7).

laboratory tests from which the relationship between resilient modulus ( $M_R$ ) and some stress parameter is determined. Review of research in this area can be found elsewhere (2,8,10-15). A stress-stiffening model is generally needed to characterize granular materials where  $M_R$  is a nonlinear function of bulk stress (sum of principal stresses). On the other hand, subgrade is characterized by a stress-softening model in which  $M_R$  is a nonlinear function of deviator stress. Uddin et al. (7) have discussed several limitations in using these procedures:

1. For certain combinations of pavement moduli, layered elastic theory predicts tensile stresses in granular layers even if gravity stresses are also considered (14). Researchers (14,16) have used a failure criterion or arbitrary procedures to overcome this problem of tensile stress.

2. There is a large scatter in  $M_R$  relationships obtained in the laboratory because of the influence of degree of saturation, water content and density, and so forth. Discrepancies may also arise from using total stress instead of effective stresses.

3. The discrepancies in current characterization procedures have been recognized (15) and attributed to laboratory  $M_R$  characterization of granular materials.

Uddin et al. (7) have discussed the possibility of using concepts developed in soil dynamics and geotechnical earthquake engineering to evaluate nonlinear moduli without using laboratory  $M_R$  relationships, as presented in the following section.

#### Equivalent Linear Analysis

Major findings from research related to the evaluation of the dynamic shear modulus ( $G$ ) for use in soil dynamics and geotechnical earthquake engineering (16-19) are summarized in the following list:

1. Shear modulus ( $G$ ) is a function of shear strain amplitude.

2. The primary parameters that affect  $G$  are shear strains ( $\gamma$ ), mean effective principal stress ( $\sigma_m$ ), void ratio ( $e$ ), number of cycles of loading ( $N$ ), and degree of saturation of cohesive soils.

3. There is a threshold strain amplitude (Figure 5) below which dynamic shear modulus is strain inde-

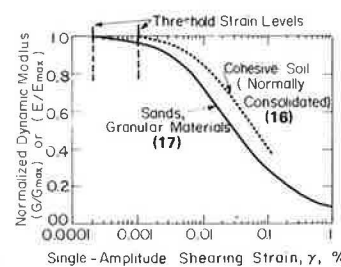


FIGURE 5 Typical relationships of normalized modulus versus shear strain for granular and cohesive soils.

TABLE 4 Maximum Shear Strain Response Under Different Loading Conditions

Loading Condition	Maximum Shear Strain <sup>a</sup> (%) from ELSYM5 Output	
	At Mid-Depth of Subbase Layer	At Top of Subgrade
Single-axle 18-kip design load <sup>b</sup>	$5.227 \times 10^{-3}$	$5.419 \times 10^{-3}$
FWD (9,000-lb peak force, radius of loading plate = 5.9 in.)	$5.592 \times 10^{-3}$	$5.683 \times 10^{-3}$
Dynaflect <sup>c</sup>	$5.381 \times 10^{-4}$	$5.729 \times 10^{-4}$

Note: The rigid pavement used in the analysis is divided as follows: top layer—portland cement concrete, 10 in. thick, 4,000,000 psi Young's modulus; 2nd layer—asphalt concrete base, 4.0 in. thick, 200,000 psi Young's modulus; 3rd layer—granular subbase, 6.0 in. thick, 75,000 psi Young's modulus; and 4th layer—subgrade, semi-infinite thickness, 30,000 psi Young's modulus.

<sup>a</sup>Largest of all values under the loading configuration.

<sup>b</sup>Dual wheels, 13.1 in. center to center; 75 psi tire pressure; 4,500 lb per wheel.

<sup>c</sup>For Dynaflect, equivalent single amplitude shear strain is half of the value given in each column.

pendent; it is typically referred to as  $G_{max}$ . Moduli associated with higher strain amplitude are strain sensitive.

4. Dynamic shear moduli data for gravelly soil are similar to that for sand, and an approximately unique curve can be obtained on a nondimensional plot of  $G/G_{max}$  versus shear strain (17), as illustrated in Figure 5. Stokoe and Lodde (16) present similar curves for cohesive soils using the resonant column test.

5. If  $G_{max}$  is known, then  $G$  associated with any higher shear strain amplitudes can be determined

from Figure 5.  $G_{\max}$  can be obtained in the field with seismic tests (like the crosshole or downhole tests) or by the surface wave technique.

These concepts can also be extended to pavement analysis because  $G$  and  $E$  are related by the following relationship for a homogeneous and isotropic material:

$$E = 2G(1 + \mu) \quad (6)$$

where  $\mu$  is Poisson's ratio.

Therefore  $G/G_{\max}$  data can be translated to  $E/E_{\max}$  data (20). The strain-softening behavior is exhibited by granular materials as well as by cohesive soils. In terms of NDT evaluations, varying strain amplitudes are associated with Dynaflect, FWD, and design loads (Table 4). It is observed that, at higher peak force levels, the peak shear strain amplitude generated by the FWD are approximately the same as those under the design load. In other words, in situ moduli derived from an FWD basin (at 9000-lb peak force) are the effective nonlinear moduli and need no further correction.

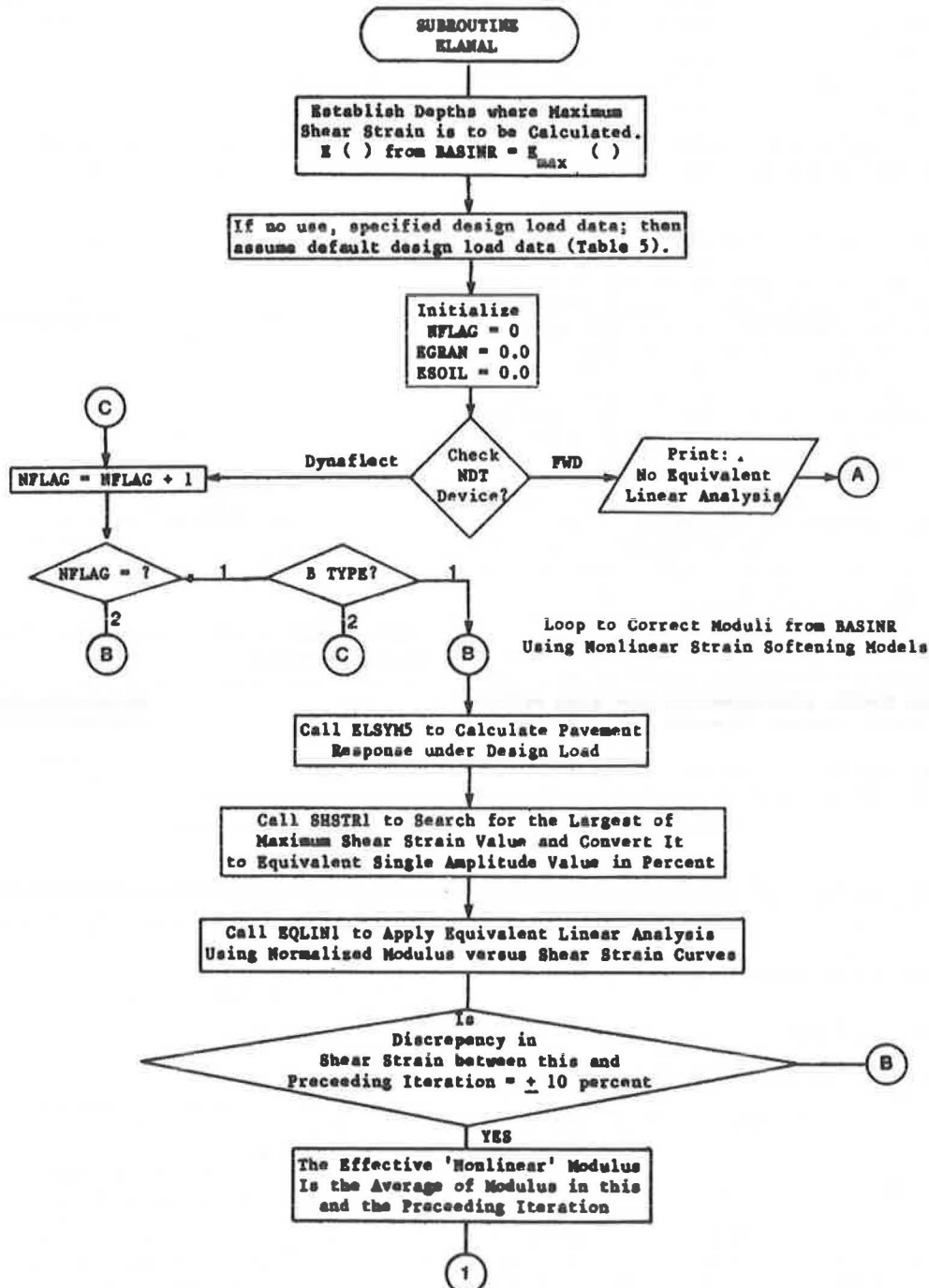


FIGURE 6 Simplified flow diagram for equivalent linear analysis to determine nonlinear strain-sensitive moduli of granular subbase and subgrade.



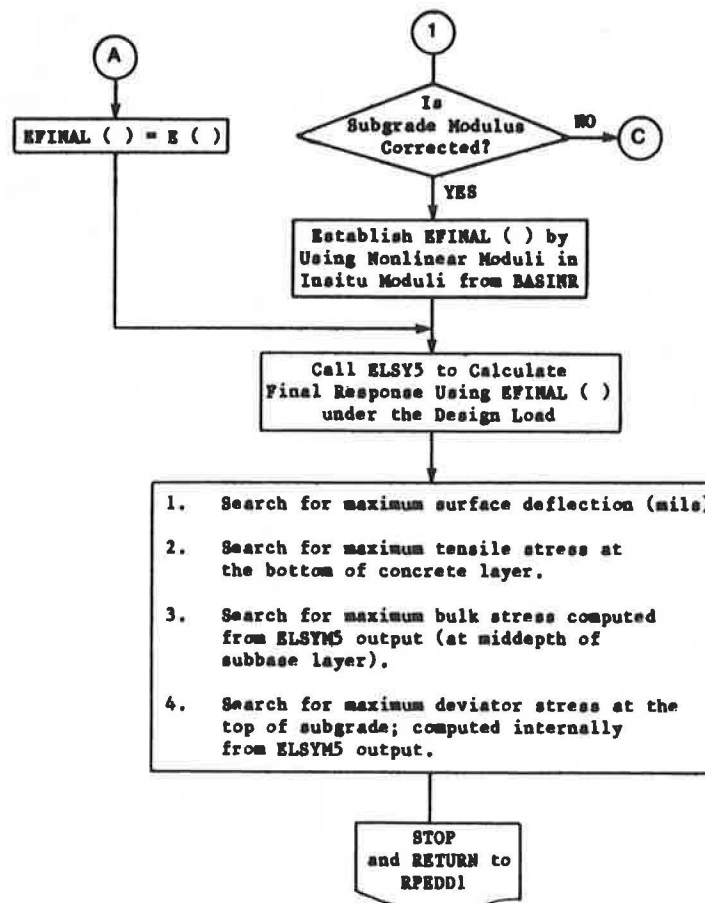


FIGURE 6 continued.

However, in situ Young's moduli calculated for nonlinear granular materials and subgrade from a Dynaflect deflection basin are associated with low amplitude shear strain and can be considered as  $E_{max}$ . A self-iterative procedure based on an equivalent linear analysis (subroutine ELANAL) has been developed for the evaluation of nonlinear moduli by using the  $E/E_{max}$  versus shear strain relationships of Figure 5. A simplified flow diagram of ELANAL is shown in Figure 6.

#### EVALUATION OF STRUCTURAL CAPACITY

Remaining life analysis is performed for the evaluation of structural capacity. ELSYM5 is called to calculate maximum horizontal tensile stress ( $\sigma_c$ ) at the bottom of the concrete layer under the design load that is then corrected for pavement discontinuities by using the critical stress parameter ( $c_p$ ) recommended by Seeds et al. (21). Past 18-kip equivalent single-axle load (ESAL) data ( $n_{18}$ ) and flexural strength data (5) are required as additional input. Remaining life analysis is based on the approach used by several researchers (1,21):

$$R_L = [1.0 - (n_{18}/N_{18})] \times 100 \quad (7)$$

where  $R_L$  is the remaining life (percent) and  $N_{18}$  is the maximum number of 18-kip ESAL applications.

$N_{18}$  is calculated by using the following equation developed for the fatigue of concrete pavement (9):

$$N_{18} = 46,000[S/(c_p \cdot \sigma_c)]^{3.0} \quad (8)$$

where  $S$  and  $\sigma_c$  are in psi.

#### APPLICATION AND IMPLEMENTATION OF PROPOSED STRUCTURAL EVALUATION SYSTEM

A simplified flow diagram of RPEDD1 is shown in Figure 7. The final output of RPEDD1 is a table, which may be detailed (with the results of the remaining life analysis) or in summary form (without traffic and remaining life data). RPEDD1 is capable of analyzing 50 deflections in one run.

The general practice of an NDT evaluation--to analyze an average deflection basin obtained from all the basins measured in a design section--is not recommended for the application and implementation of RPEDD1. Figure 8 shows an example of analyzing deflection basins measured on a CRC pavement. The evaluation of individual deflection basins provides the user with a global look at the tested pavements. The tabulated results, printed in output, can be plotted as shown in Figure 9. A remaining life profile (Figure 9, top) can be used to identify sections that should be considered for an overlay analysis if the remaining life is below a threshold limit (e.g., 40 percent). Plots of subgrade modulus (Figure 9, bottom) can be used to delineate design sections. Finally, design moduli based on mean and standard deviations in each design section can be

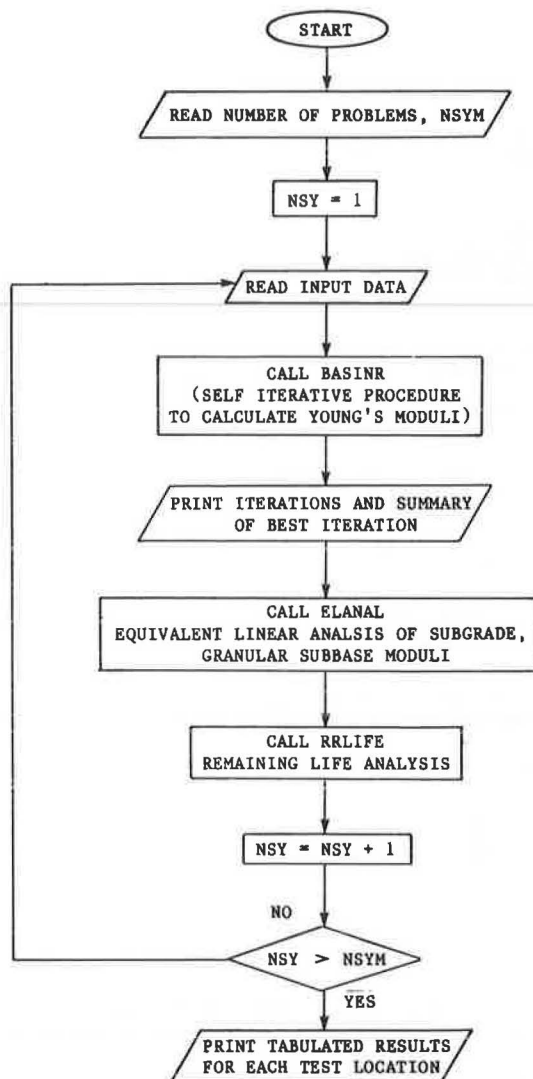


FIGURE 7 Simplified flowchart of RPEDD1.

determined for later use in a mechanistic overlay and rehabilitation design program such as RPRDS (21).

#### CONCLUSIONS

A complete framework for NDT evaluation of rigid pavements has been presented in this paper. The computer program RPEDD1 has been developed in this study for evaluation of dynamic deflection basins measured by the Dynaflect or the FWD. The principal conclusions based on the research presented in this paper are as follows:

1. The self-iterative model yields unique moduli, is not user dependent, and eliminates guesswork in assuming seed moduli.
2. NDT evaluation of nonlinear moduli of granular and cohesive materials using the concept of strain sensitivity is a rational approach. It also eliminates the derivation of laboratory  $M_R$  relationships.
3. Guidelines for the application and implementation of RPEDD1 provide the user with a global look at the structural condition of pavement, variability of in situ moduli along the pavement, overlay analysis, selection of design sections, and design moduli for later use in comprehensive overlay design.

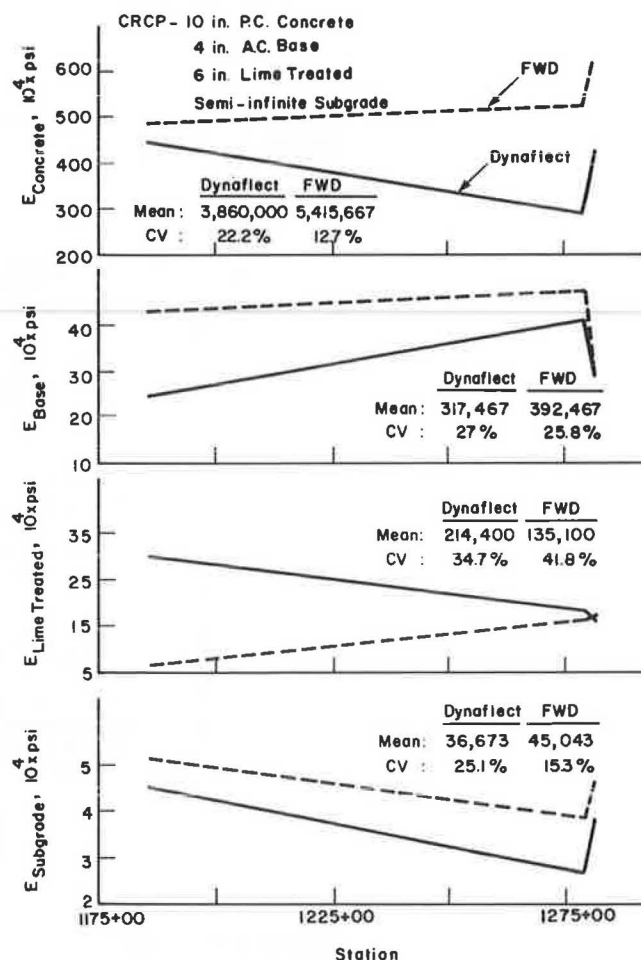


FIGURE 8 Evaluation of in situ moduli from deflection basins measured on a CRC pavement (SH-71) at Columbus, Texas.

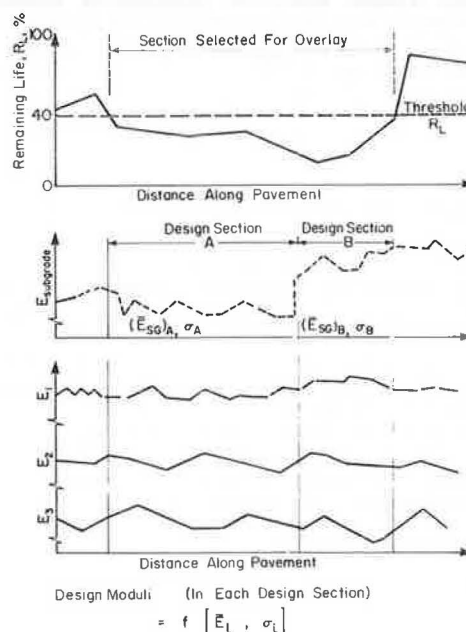


FIGURE 9 Application and implementation of RPEDD1.



Using a similar approach, another computer program, FPEDD1--a flexible pavement structural evaluation system based on dynamic deflections--has been developed; it is described elsewhere (7).

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