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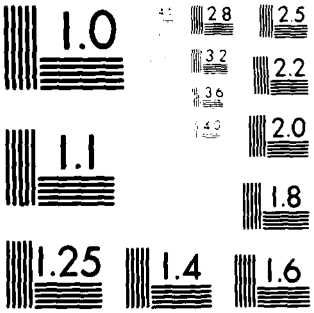

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Report No. FAA-RD-80-9-II

LEVEL III

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NONDESTRUCTIVE TESTING FOR LIGHT AIRCRAFT PAVEMENTS

PHASE II

Development Of The Nondestructive Evaluation Methodology

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16. Abstract

This study is the second phase of a two-phase program to develop a nondestructive pavement evaluation method to evaluate pavements designed to support aircraft with gross weights of less than 30,000 lb. A methodology that uses the deflection basin from nondestructive testing (NDT) to predict the elastic moduli of up to four pavement layers was developed. A computer program (CHEVDEF) was developed that predicts the moduli so that the deflection basin from a layered elastic solution approximates the measured basin. The nonlinear stress-dependent characteristics of the subgrade are defined. Moduli derived from NDT results are used in the PAVEVAL program developed in ~~an~~ earlier study (FAA-RD-77-186-I) by R. A. Weiss to predict the allowable aircraft loads. The subgrade elastic moduli described by this method compares well with laboratory test results and with results from other methodologies. The predicted allowable load from this method compares well with the allowable load from the dynamic stiffness modulus procedure.

Appendix A presents a laboratory procedure for determining the resilient modulus of subgrade soils, Appendix B discusses the CHEVDEF program, and Appendix C presents a guide to the use of the ~~computer program~~ PAVEVAL.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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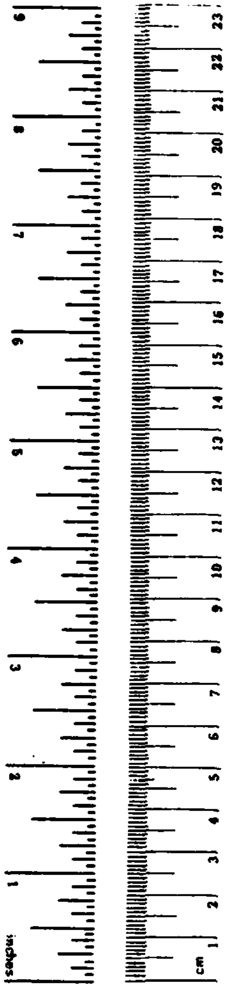
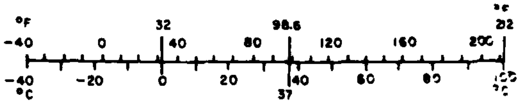
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This study, the second phase of a two-phase program, was sponsored by the Federal Aviation Administration through Inter-Agency Agreement No. DOT FA78WAI-848, "Nondestructive Testing for Light Aircraft Pavements." Phase I of the study was conducted during the period April 1978 - July 1979 and was reported in FAA Report No. FAA-RD-80-9, "Nondestructive Testing for Light Aircraft Pavements; Phase I, Evaluation of Nondestructive Testing Devices." Phase II was conducted during the period August 1979 - August 1980 under the direction of Mr. J. P. Sale, Chief (retired), Geotechnical Laboratory (GL); Dr. D. C. Banks, Acting Chief, GL; Dr. P. F. Hadala, Assistant Chief, GL; Messrs. R. L. Hutchinson, Chief, Pavement Systems Division (PSD); A. H. Joseph, Acting Chief, PSD; and J. W. Hall, Jr., Chief, Prototype Testing and Evaluation Unit, PSD, of the U. S. Army Engineer Waterways Experiment Station (WES). Dr. Walter R. Barker and Messrs. P. S. McCaffrey, Jr., R. D. Curtis, and A. J. Bush III actively participated in the study. The report was prepared by Mr. Bush.

Director of the WES during the conduct of the investigation and preparation of this report was COL Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

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INTRODUCTION

BACKGROUND

Nondestructive testing (NDT) devices are being widely used to evaluate the load-carrying capability of pavements for air carrier and highway pavements. Evaluation procedures have been developed using various types of NDT devices for these pavements. Phase I[1] of this study evaluated commercially available NDT devices for use on light aircraft pavements (design gross loadings less than 30,000 lb). Phase II, reported herein, is to develop a methodology for evaluation of light aircraft pavements based upon multilayered elastic models and limiting stress/strain criteria.

PURPOSE

The purpose of Phase II of this study is to develop an evaluation procedure based on a multilayered elastic procedure for evaluating pavements that support aircraft with gross weights of less than 30,000 lb. The evaluation will determine the allowable gross aircraft load for a given number of operations.

SCOPE

This study will utilize data only from nondestructive testing devices similar to the Model 2008 Road Rater. Although concepts for the model are general and would probably apply to any of the other devices evaluated in the Phase I study, this device alone was used in development of the evaluation methodology.

DEVELOPMENT OF THE EVALUATION METHODOLOGY

REVIEW OF NDT EVALUATION PROCEDURES

Since a number of NDT pavement evaluation procedures have been developed, a cursory review will be made to outline the confines for which this methodology was restricted.

Green and Hall[2] reported a procedure that uses the U. S. Army Engineer Waterways Experiment Station (WES) 16-kip vibrator. This procedure uses a dynamic load sweep at a constant frequency of 15 Hz. Only the center deflection is measured and the resultant parameter (dynamic stiffness modulus (DSM)) is computed as the inverse slope of the upper third of the load deflection relationship. The DSM is correlated directly with allowable single-wheel load. The procedure utilizes the U. S. Army Corps of Engineer (CE) California Bearing Ratio (CBR) design for flexible pavements and the Westergaard theory for rigid pavements.

Weiss[3] reported a layered elastic evaluation procedure using results from the WES 16-kip vibrator. This procedure is used to predict the subgrade modulus. Since the Model 2008 Road Rater produces a 4000-lb peak load (8000-lb peak to peak) as compared with 15,000-lb peak for the WES 16-kip vibrator, this procedure could not be readily adapted.

Yang[4] reported a procedure that uses the WES 16-kip vibrator and a frequency sweep where the dynamic load is held constant and the frequency is varied between approximately 5 and 50 Hz. This procedure predicts the subgrade modulus.

The frequency sweep test requires approximately 10 times the amount of time to conduct as a load sweep. WES research indicates that the data derived from a frequency sweep do not warrant the extra time required to collect. Pavement material properties are frequency-dependent. Therefore, another variable is introduced to the evaluation method that must be accounted for.

Treybig et al.[5] reported a layered elastic evaluation/overlay design procedure using the Dynaflect testing device. In this procedure, the modulus values of the upper layers are assumed. Samples are taken of the granular base and subbase and subgrade materials, which are tested in the laboratory using a dynamic load triaxial test to determine the resilient modulus. By use of the deflection from the number one sensor of the Dynaflect and assumed or laboratory modulus values, the modulus of the subgrade is determined through a series of nomographs. This modulus is compared with the laboratory results of resilient modulus versus deviator stress. Through a series of approximations of stress and modulus that parallels the laboratory relationship, the design modulus is predicted. The basic concepts of the Treybig procedure are similar to the approach being reported except that a goal in developing this procedure is not to require destructive sampling and laboratory testing.

Koole[6] reported a layered elastic evaluation/overlay design procedure using the Falling Weight Deflectometer. The deflection at the center of the applied load and the ratio of that deflection to a deflection some distance away from the applied load were used. The pavement was characterized by a three-layer system. The subgrade modulus and either the asphaltic concrete (AC) modulus or the AC thickness are determined in this procedure. The modulus values for the AC layer (if the thickness is to be determined) and layer 2 are determined from laboratory results or from construction records. The effective thickness of the surface layer is determined. From these values, the layered elastic theory is used to predict allowable or overlay requirements.

Anani[7] reported results using the Model 400 Road Rater. The Model 400 Road Rater, described in detail in Phase 1 of this study, applies a peak-to-peak dynamic load of approximately 720 lb to the pavement through two 4- by 7-in. pads spaced 6 in. apart. Four sensors are used to monitor deflections. One is located between the pads while the other three are spaced at 1-ft intervals.

Anani used the BISAR computer program developed by the Shell Oil Company with successive approximation techniques to determine the elastic moduli of the pavement layers. Using up to a four-layer system, the procedure approximated the E values by the following equation:

$$E(I)_{new} = E(I)_{old} \times \frac{RRD(I) + \Delta(I)}{2} RRD(I)$$

where

$E(I)_{new}$ = modulus value for layer I
$E(I)_{old}$ = previous assumed modulus value for layer I
$RRD(I)$ = measured deflection corresponding to layer I, i.e., deflection No. 4 is dependent on layer 4 and deflection No. 3 is dependent on layer 3, etc.
$\Delta(I)$ = deflection from BISAR associated with $E(I)_{old}$.

Other procedures have been developed by Sharpe[8] and Ullidtz[9] that predict modulus values for pavement systems using the layered theory and nondestructive testing devices. These procedures use two deflection measurements from the deflection basin.

As shown above, a number of researchers used nondestructive testing and the layered elastic theory to evaluate and design overlays for pavements. The procedure developed in this study will incorporate some of the stronger points of those procedures as well as add some new approaches.

EXPERIMENTAL DATA

The data used in developing this procedure were collected on the Pennsylvania Transportation Research Facility (PTRF) and on selected pavements at the WES. The PTRF is a one-mile track located at Pennsylvania State University. Fifteen items were tested with the Model 2008 Road Rater in June 1978. From 1 to 20 tests were conducted on each item. The deflections used in this study will be the average of those tests. These averages are given in Table 1 for the 7000- and 5000-lb force levels. The pavement structures of the 15 items are given in Table 2. Also shown in Table 2 are the number of equivalent 18-kip axle loads (EAL) that were applied to the pavement items prior to testing. The surface conditions of the items were good except for items 3, A, and C. These items exhibited some surface distress such as longitudinal and alligator cracking.

Two test pits were excavated in the PTRF to obtain samples of the granular subbase material and the subgrade. Undisturbed block samples and bag (disturbed) samples were taken of the subgrade. Bag samples were also taken of the subbase. Resilient modulus tests were conducted

Table 1

Model 2008 Road Rater Deflections on PTRF Items

for 7000- and 5000-lb Loads

Item	No. of Tests	Mean Pavement Temperature, °F	7000-lb Load: Mean Peak-Peak Force, lb	7000-lb Load: Mean Deflection, mils D_1	D_2	D_3	D_4	5000-lb Load: Mean Peak-Peak Force, lb	5000-lb Load: Mean Deflection, mils D_1	D_2	D_3	D_4
1A	12	73.9	7246.0	5.9	4.43	3.07	1.93	5127.0	3.79	2.63	1.56	1.18
Std Dev			175.0	0.95	0.55	0.81	0.57	151.0	1.01	0.24	0.26	0.15
Coeff Var, %			2.4	16.1	12.4	26.4	29.3	0.03	26.6	[illegible]	14.2	12.9
1B	14	90.4	6936.0	6.74	4.98	2.71	1.58	4988.0	4.33	3.17	1.77	0.98
Std Dev			245.0	0.46	0.40	0.22	0.49	129.0	0.80	0.34	0.22	0.17
Coeff Var, %			3.5	6.8	8.0	8.0	3.1	0.03	18.5	10.7	12.3	17.0
2	11	85.0	7016.0	5.79	4.34	2.44	1.14	4988.0	3.66	2.56	1.47	0.75
Std Dev			36.0	0.47	0.37	0.25	0.12	80.0	0.36	0.89	0.52	0.27
Coeff Var, %			0.5	8.0	8.5	10.3	10.6	0.02	9.8	34.9	35.3	35.7
3	10	96.5	7030.0	11.3	8.17	3.70	1.93	5012.0	6.92	5.21	2.23	1.03
Std Dev			33.0	1.54	1.17	0.92	0.91	47.0	0.87	0.82	0.41	0.29
Coeff Var, %			0.4	13.6	14.3	24.9	47.3	0.01	12.5	15.8	18.2	27.9
4	11	97.5	7015.0	3.26	2.92	2.39	1.81	4035.0	2.15	1.93	1.55	1.15
Std Dev			29.0	0.93	0.80	0.79	0.68	30.0	0.57	0.51	0.48	0.39
Coeff Var, %			0.4	28.7	27.5	33.2	37.4	0.01	26.4	26.6	31.4	33.7
5	11	95.1	7032.0	7.60	5.39	2.77	1.54	5018.0	4.66	3.47	1.85	1.05
Std Dev			23.0	0.53	0.70	0.68	0.47	66.0	0.37	0.37	0.27	0.23
Coeff Var, %			0.3	7.0	13.1	24.6	30.3	0.01	7.9	10.7	14.4	22.4
6	11	80.2	7040.0	4.56	3.66	2.47	1.61	5011.0	2.91	2.55	1.62	1.09
Std Dev			32.0	0.62	0.67	0.33	0.25	50.0	0.45	0.66	0.23	0.21
Coeff Var, %			0.5	13.5	18.3	13.4	15.6	0.01	15.6	25.8	13.9	19.1

(Continued)

Note: 1°F = -17°C; 1 lbf = 4.448 N; 1 mil = 25.4 microns.

Table 1 (Concluded)

Item	No. of Tests	Mean Pavement Temperature, °F	7000-lb Load					5000-lb Load				
			Mean Peak-Peak Force, lb	Mean Deflection, mils				Mean Peak-Peak Force, lb	Mean Deflection, mils			
				D_1	D_2	D_3	D_4		D_1	D_2	D_3	D_4
7	1	77.3	7090.0	4.40	3.30	2.30	1.50	5130.0	3.00	2.20	1.50	1.00
Std Dev			--	--	--	--	--	--	--	--	--	--
Coeff Var, %			--	--	--	--	--	--	--	--	--	--
8	19	80.8	7103.0	9.03	6.15	3.11	1.57	5026.0	5.46	3.94	1.75	0.98
Std Dev			106.0	1.21	0.70	0.84	0.68	73.0	0.90	0.65	0.18	0.30
Coeff Var, %			1.5	13.4	11.4	27.2	43.6	0.01	16.6	16.5	10.5	30.3
A	14	87.1	7116.0	10.60	8.94	3.56	1.75	5044.0	6.34	5.12	2.32	1.04
Std Dev			202.0	2.61	2.71	0.72	0.57	86.0	1.29	1.05	0.44	0.37
Coeff Var, %			2.8	24.6	24.3	20.3	32.6	0.02	20.4	20.5	18.9	35.9
B	12	85.0	7087.0	3.53	2.98	2.18	1.50	5159.0	2.47	2.08	1.50	0.98
Std Dev			56.0	0.35	0.35	0.13	0.13	103.0	0.28	0.24	0.11	0.20
Coeff Var, %			0.7	9.8	11.7	5.8	8.5	0.02	11.3	11.7	7.5	20.6
C	9	82.2	7028.0	12.16	8.48	2.79	1.33	5051.0	7.18	5.05	1.80	0.86
Std Dev			43.0	3.97	2.68	0.44	0.33	108.0	2.07	1.32	0.17	0.12
Coeff Var, %			0.6	32.6	31.6	15.6	25.1	0.02	28.9	26.1	9.4	13.8
E	11	82.4	7236.0	9.37	6.74	2.78	1.29	5076.0	5.45	3.99	1.81	0.92
Std Dev			118.0	0.72	0.59	0.34	0.16	101.0	0.47	0.31	0.18	0.11
Coeff Var, %			1.6	7.6	8.8	12.2	12.7	0.02	8.6	7.8	9.9	12.1
F	12	77.5	7019.0	7.66	5.88	2.76	1.36	5053.0	4.9	3.81	1.85	0.92
Std Dev			45.0	0.72	0.52	0.18	0.25	35.0	0.5	0.35	0.15	0.12
Coeff Var, %			0.6	9.5	8.8	6.6	18.4	0.01	10.1	9.2	7.8	12.0
G	12	74.0	7022.0	8.01	6.33	3.10	1.51	5010.0	4.93	3.89	1.96	0.97
Std Dev			23.0	0.62	0.53	0.30	0.17	49.0	0.38	0.34	0.21	0.14
Coeff Var, %			0.3	7.8	8.3	9.5	11.5	0.01	7.8	8.7	10.6	14.9

Table 2

Pavement Characteristics for PTRF Items

	Layer No. 1		Layer No. 2		Layer No. 3		Layer No. 4		EAL
Item	Thickness in.	Type	Thickness in.	Type	Thickness in.	Type	Thickness in.	Type	at Time of Test
1A	7.5	Bituminous concrete	20.5	Subbase	--	Subgrade			1,797,000
1B	7.5	Bituminous concrete	14.0	Subbase	--	Subgrade			2,386,000
2	8.5	Bituminous concrete	8.0	Subbase	--	Subgrade			2,386,000
3	2.5	Bituminous concrete	8.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	2,386,000
4	2.5	Bituminous concrete	8.0	Aggregate cement	8.0	Subbase	--	Subgrade	2,386,000
5	2.5	Bituminous concrete	8.0	Aggregate bituminous	8.0	Subbase	--	Subgrade	2,386,000
6	10.5	Bituminous concrete	8.0	Subbase	--	Subgrade			2,386,000
7	9.5	Bituminous concrete	8.0	Subbase	--	Subgrade			2,386,000
8	8.0	Bituminous concrete	8.0	Subbase	--	Subgrade			1,303,000
A	2.5	Bituminous concrete	4.0	Aggregate cement*	8.0	Subbase	--	Subgrade	1,303,000
B	2.5	Bituminous concrete	6.0	Aggregate cement*	8.0	Subbase	--	Subgrade	1,303,000
C	2.5	Bituminous concrete	6.0	Aggregate cement**	8.0	Subbase	--	Subgrade	1,303,000
E	4.0	Bituminous concrete	8.0	Crushed stone	8.0	Subbase	--	Subgrade	309,000
F	5.5	Bituminous concrete	6.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	309,000
G	5.5	Bituminous concrete	4.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	309,000

Note: 1 in. = 2.54 cm.

* Limestone aggregate.

** Slag aggregate.

on these samples in accordance with the procedures outlined in Appendix A. Average results of the subgrade tests are presented in Figure 1. It should be noted that undisturbed samples gave higher modulus values than disturbed samples. The granular subbase results are presented in Figure 2.

RELATIONSHIP OF LAYERED ELASTIC THEORY TO MEASURED DEFLECTIONS

GENERAL

The first assumption in developing this procedure is that dynamic deflections correspond to those deflections predicted from the layered elastic theory. To validate this assumption experimental data were compared with results from two computer programs. The first is the Shell BISAR computer program, based on the layered elastic theory, which relates stress and strain in each layer to a load applied at the surface of a pavement. The other program, entitled CHEVIT,[10] gives a nonlinear approach to the solution of the modulus of the lower layers by using laboratory stress-modulus relationships for granular and subgrade layers. Those layers are divided into sublayers for which the stress is calculated initially, and from the laboratory stress-modulus relationship a new modulus is computed. With this modulus, the program again computes the stress. The program iterates until a solution is obtained for modulus and stress.

LINEAR ANALYSIS

To determine the applicability of the deflection basin to the layered elastic analysis, the BISAR computer program was initially used. The modulus values for the AC surface layers were obtained from the 16-Hz relationship[11] presented in Figure 3. An evaluation of data collected with the WES 16-kip vibrator on specially constructed temperature sections at the WES was made using the 16-Hz modulus versus temperature relationships. The test sections were small (approximately 20 by 20 ft) and consisted of varying thickness of AC over a lean clay (CL) subgrade. The design of these sections considered the thickness of AC to be the only variable. Tests were conducted over a wide range of temperatures. Modulus values for the AC as determined from Figure 3 were used in the

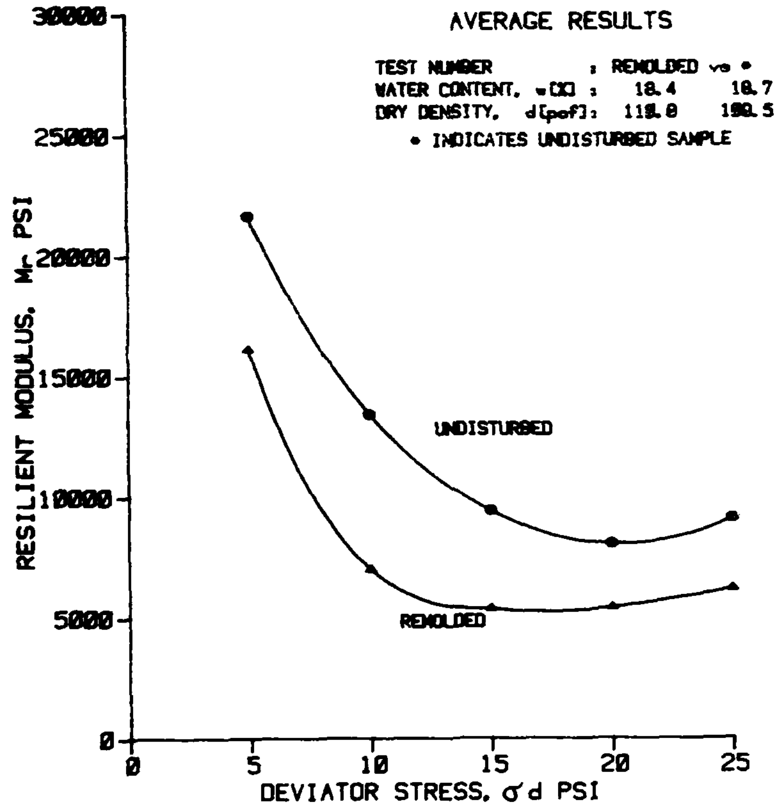


Figure 1. Average results of resilient modulus tests on PTRF subgrade material (1 psi = 703 kg/m^2)

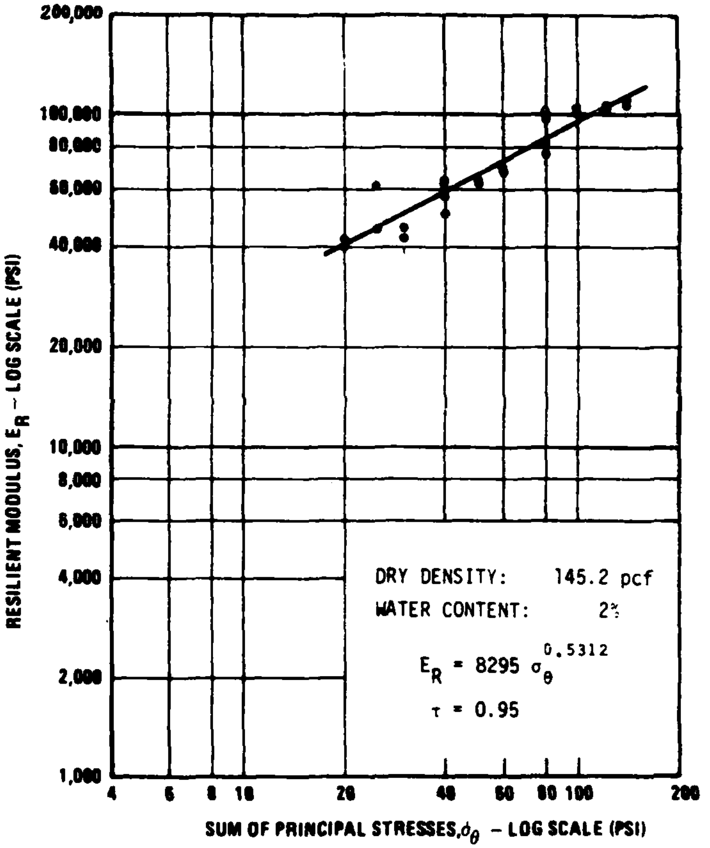


Figure 2. Results of resilient modulus tests on PTRF subbase material (1 psi = 703 kg/m^2; 1 pcf = 16.02 kg/m^3)

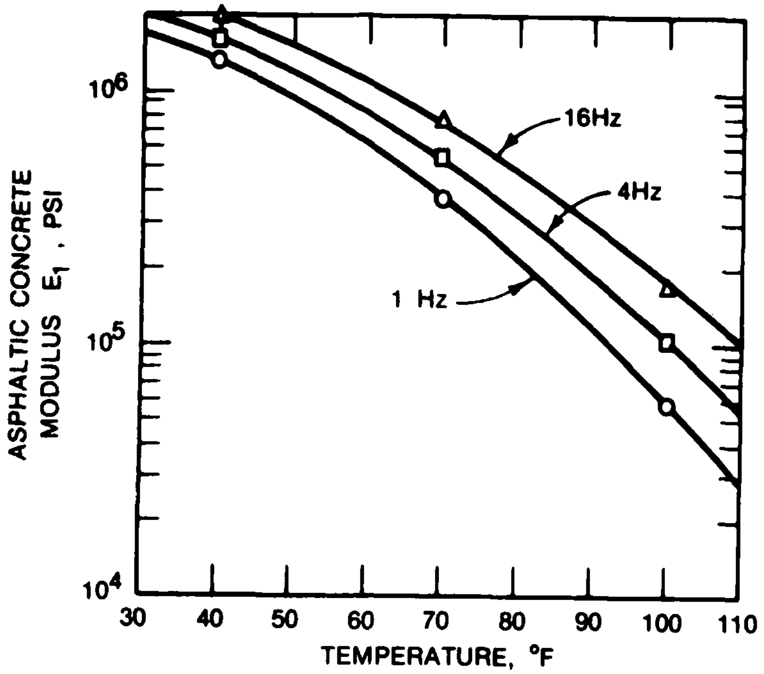


Figure 3. Modulus-temperature relationships for AC surfacing (1 psi = 703 kg/m^2; $1^oF = -17^oC$) (after Kingham and Kallas[11])

BISAR program to predict deflections. Good correlation was obtained for the temperature test section between the deflection ratios (deflection at a given temperature to deflection at 70^oF) obtained from the experimental results and the results from the BISAR. Therefore, the relationships presented in Figure 3 were selected for determination of the AC modulus values.

Modulus values for the pavement layers other than the AC surface layers of the PTRF were estimated from construction data and based on laboratory results that were collected during the initial construction (not the laboratory results presented in this report). Poor agreement was obtained between the BISAR deflections and the measured deflections for the PTRF sections. Therefore, it was concluded that it is extremely difficult to estimate correct modulus values for pavement layers that have been subjected to extensive traffic and environmental effects.

NONLINEAR ANALYSIS

An analysis was then made using the CHEVIT nonlinear program.

The granular subbase layer was characterized by the laboratory relationships shown in Figure 2. The subgrade resilient modulus relationships in Figure 4 represent the averages of the undisturbed sample tests. Figure 5 shows a typical pavement section (PTRF item 1A). The initial estimate for the modulus of the nonlinear layers, as well as the modulus for the linear layer, is given. Pavement sections for all of the PTRF items are shown in Table 2.

The summation of the strains in the bottom layer to infinity by the layered elastic model tends to give larger deflections than the measured values. To compensate for this effect, a rigid layer was placed in this system model at a depth of 20 ft below the surface. Figure 6 shows a comparison of predicted deflections with and without the rigid boundary to the measured deflections. Note that the basins predicted from CHEVIT using the rigid layer agree better with the Model 2008 Road Rater basins than those predicted without the rigid layer.

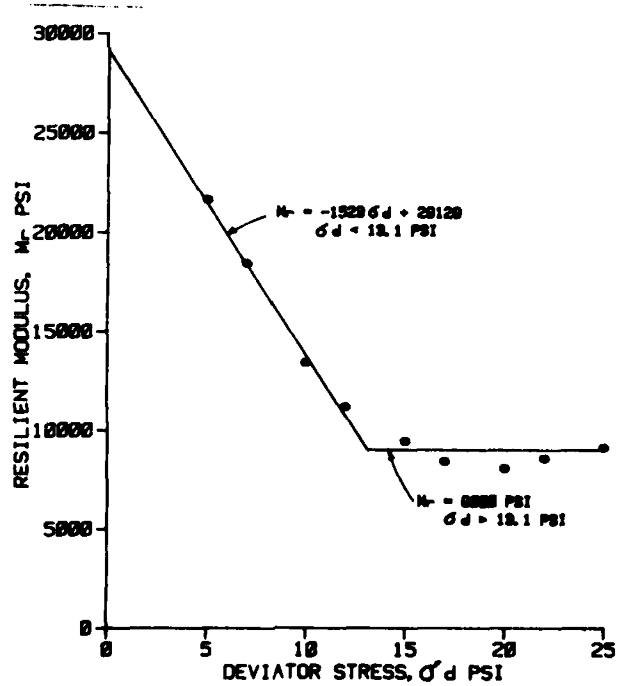


Figure 4. Relationship of subgrade resilient modulus and deviator stress used in CHEVIT (1 psi = 703 kg/m2)

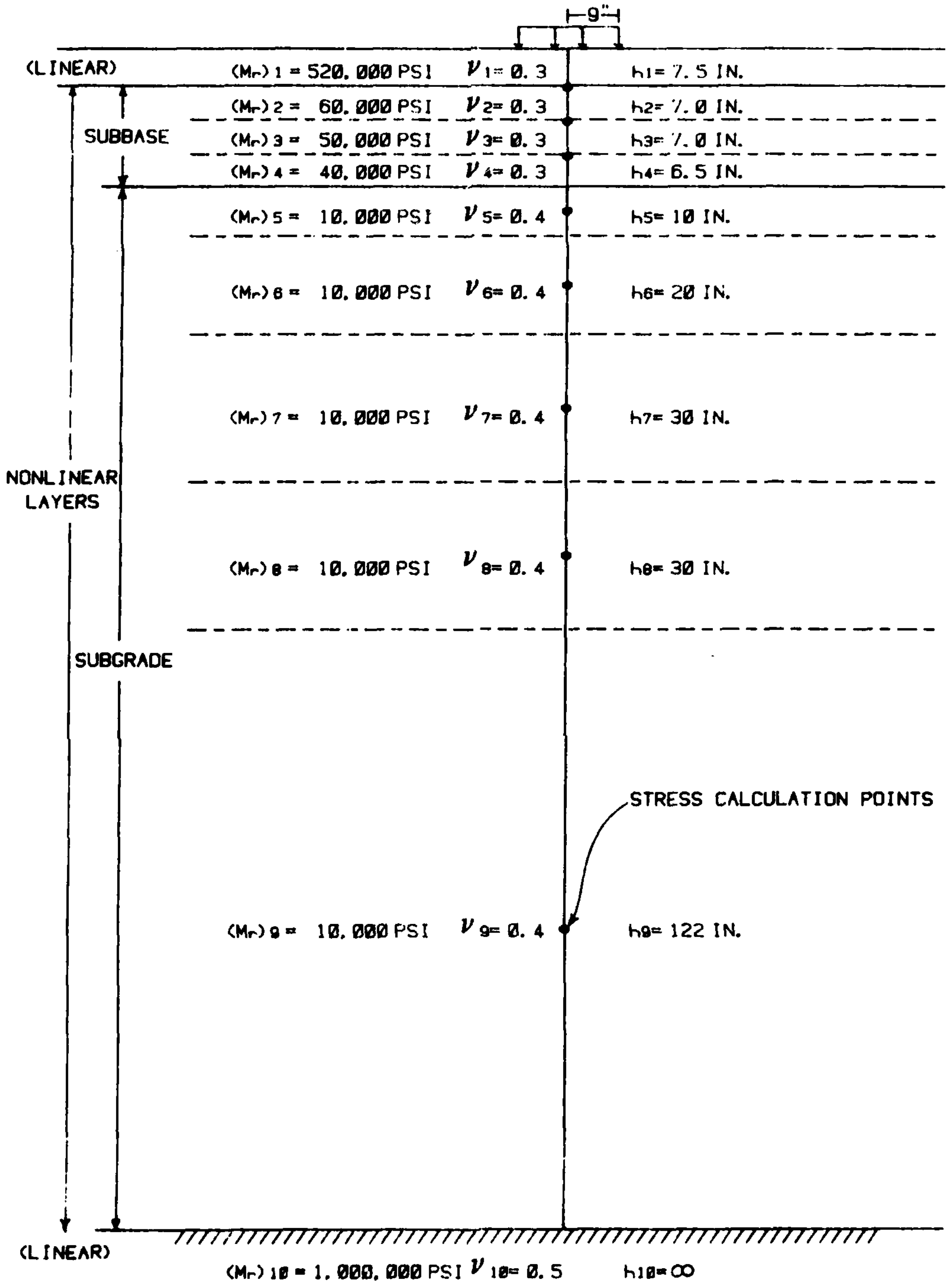


Figure 5. PTRF item 1A pavement section breakdown for CHEVIT input (1 in. = 2.54 cm; 1 psi = 703 kg/m^2)

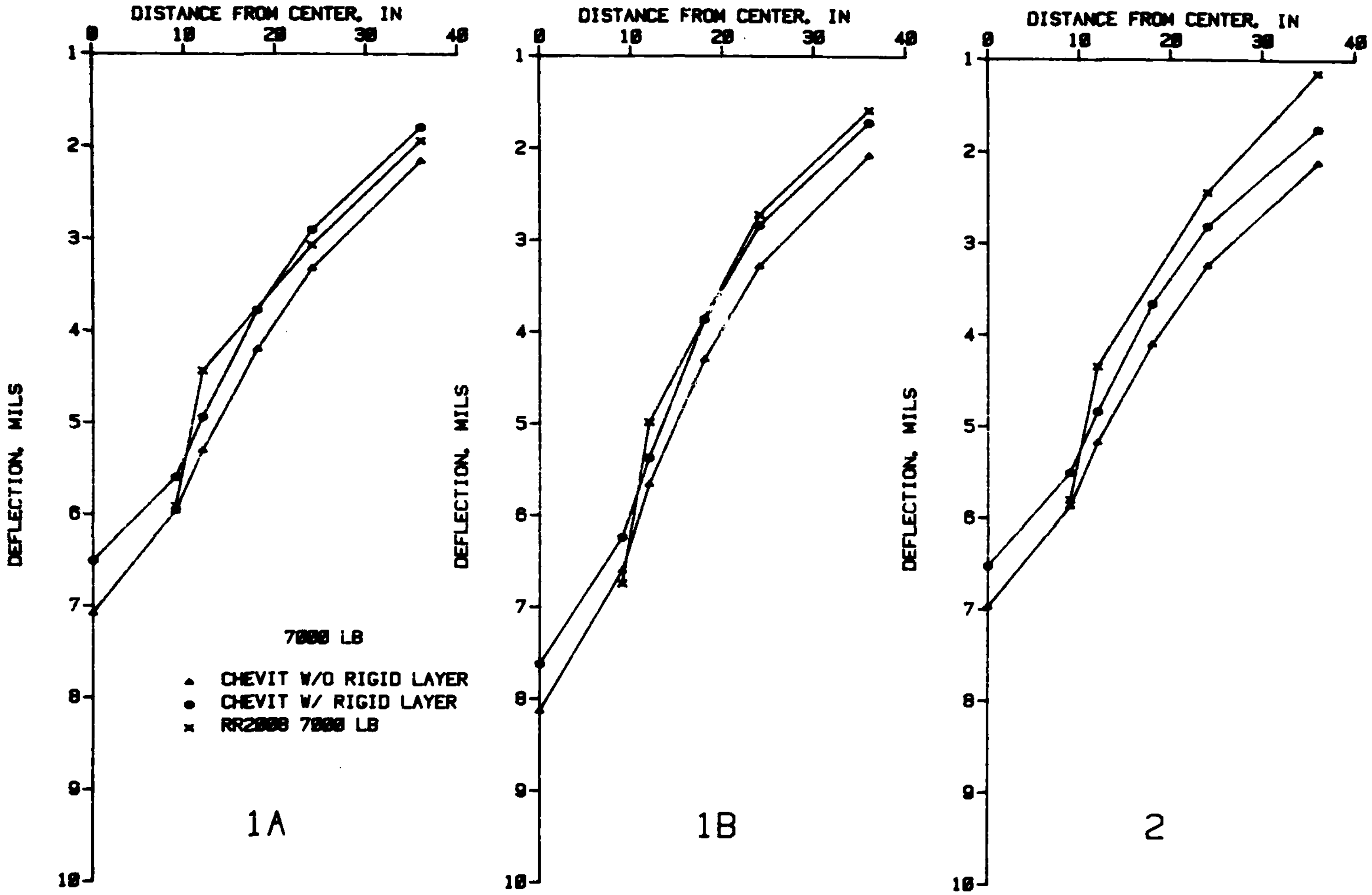


Figure 6. Comparison of layered-elastic deflection basins with and without rigid layer to measured basins (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

Basins are shown for each of the 15 test items of the PTRF in Figures 7 through 11. Tests with both 5000- and 7000-lb loads were conducted and compared with CHEVIT results. Note the good agreement in the basin data for those sections without the lime and cement-treated base courses. The modulus values for the lime and cement-treated layers were taken from construction records. The heavy traffic on the PTRF at the time of test apparently resulted in cracking of these stabilized layers. Therefore, the stabilized layers had much lower moduli values at the time of the test than those values used in the CHEVIT analysis. This fact explains the variance in measured and predicted deflections in items 3, A, C, E, F, and G shown in Figures 8, 10, and 11. From the results, it appears that the deflection basin is a measurement that can be modeled with a layered elastic theory and, therefore, used to predict the strength parameters of the pavement layers.

EFFECTS OF STATIC PRELOAD

The effects of the static load applied to the pavement surface as a preload with the Model 2008 Road Rater were analyzed using the CHEVIT program. Figure 12 illustrates loading versus time for the Model 2008 Road Rater for the 5000- and 7000-lb tests. The sinusoidal loading applies a minimum and a maximum force to the pavement surface. The magnitudes of these forces range from 500 to 6500 lb for the 5000-lb peak-to-peak force level and from 500 to 7500 lb for the 7000-lb peak-to-peak force. The CHEVIT program was run with forces of 6500 and 1500 lb, and the differences (diff) in predicted deflections from each run were calculated to model the sinusoidal loading of the Road Rater. The results were compared to a run where the force was 5000 lb. Table 3 shows the results of these calculations for PTRF items 1A, 1B, and 2. A maximum difference of 6.3 percent occurred at the 5000-lb force level at 12 in. from the center of the load; however, the percent difference was practically negligible for most comparisons. This analysis indicates that the effect of the static load for computer modeling of the Road Rater results is negligible particularly when the vibrator is operated near the maximum output. Therefore, the static load will be neglected in the determination of the layer modulus values.

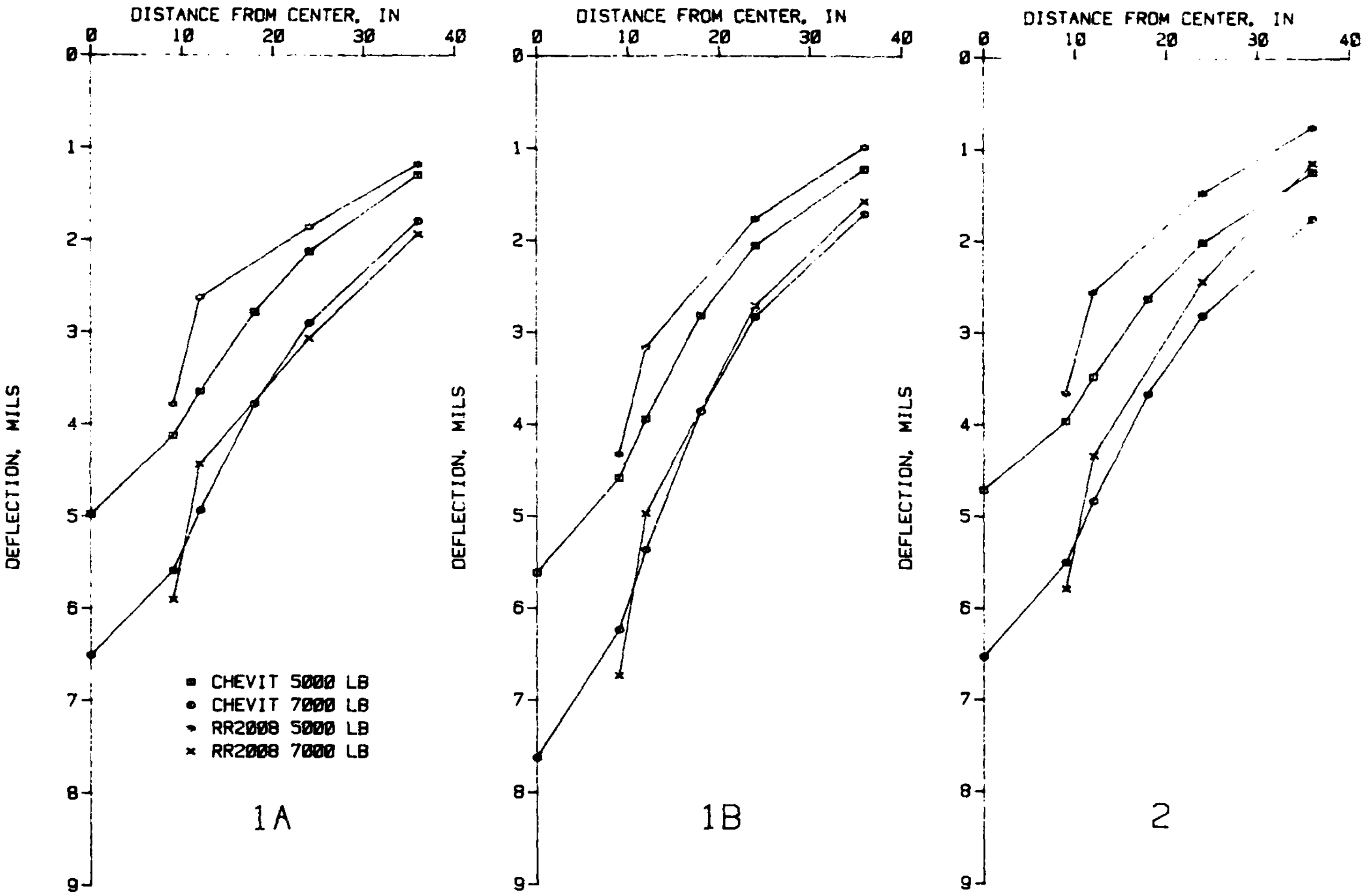


Figure 7. Predicted and measured basins on PTRF items 1A, 1B, and 2 (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

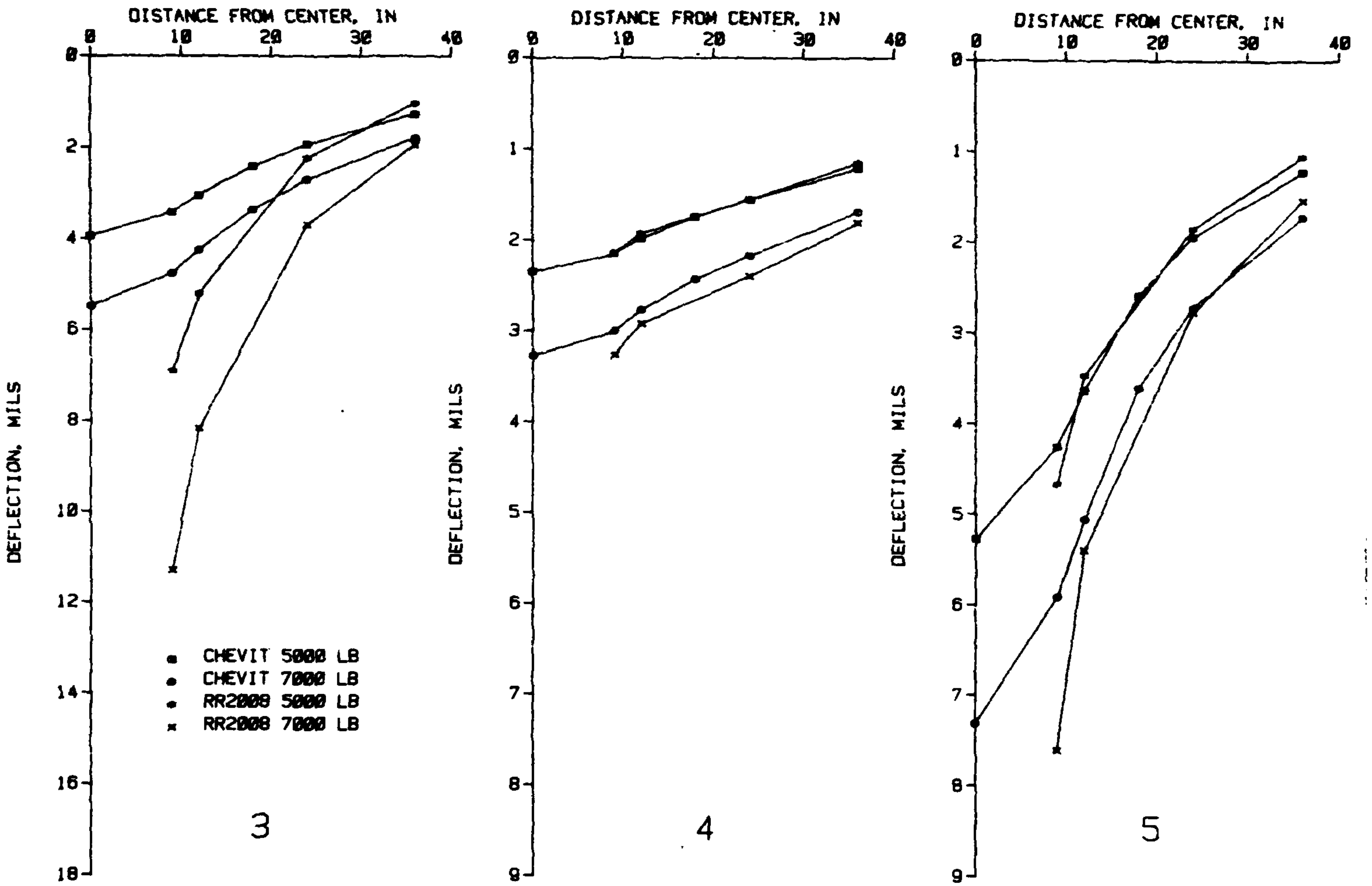


Figure 8. Predicted and measured basins on PTRF items 3, 4, and 5
(1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

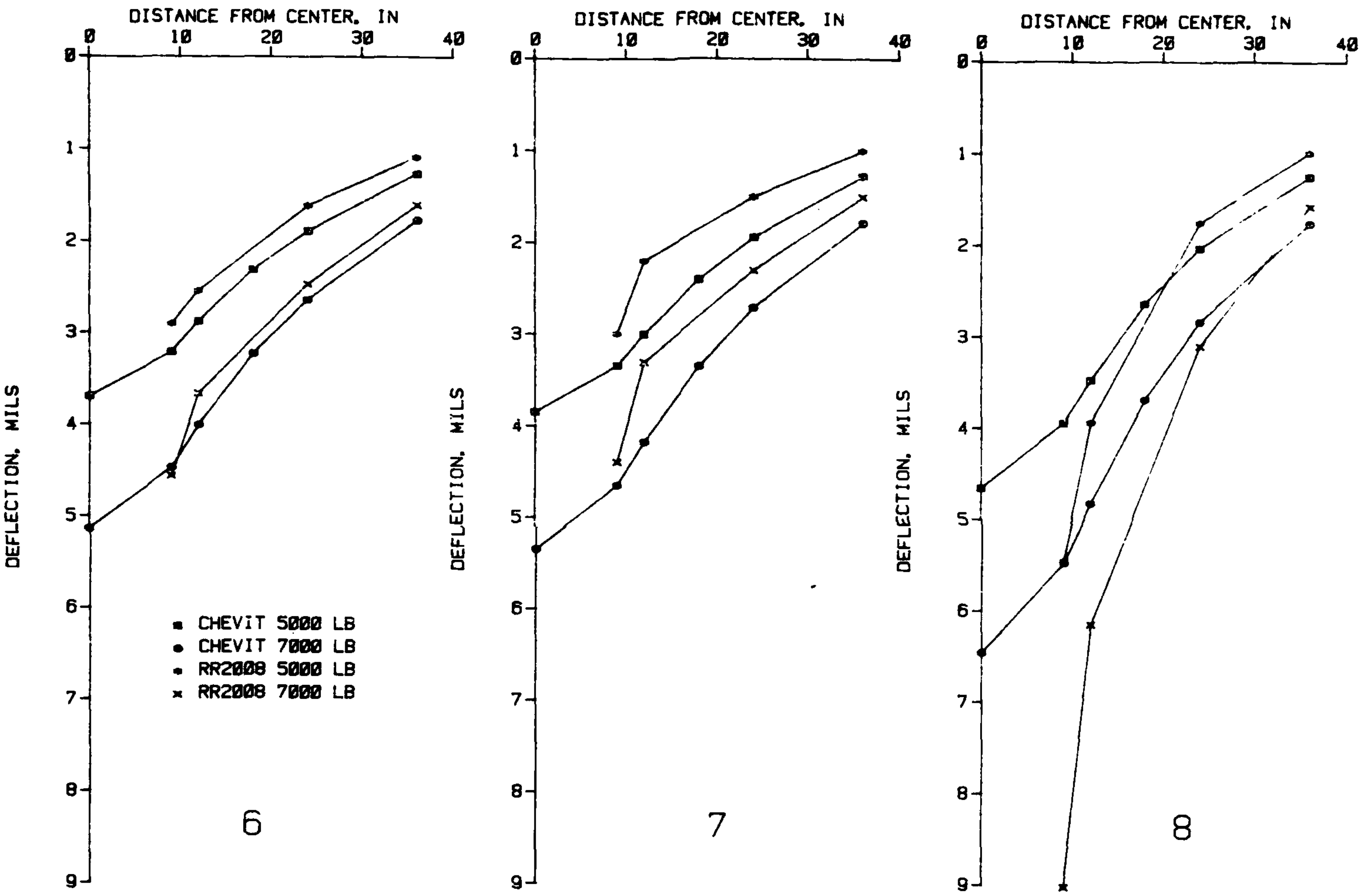


Figure 9. Predicted and measured basins on PTRF items 6, 7, and 8 (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

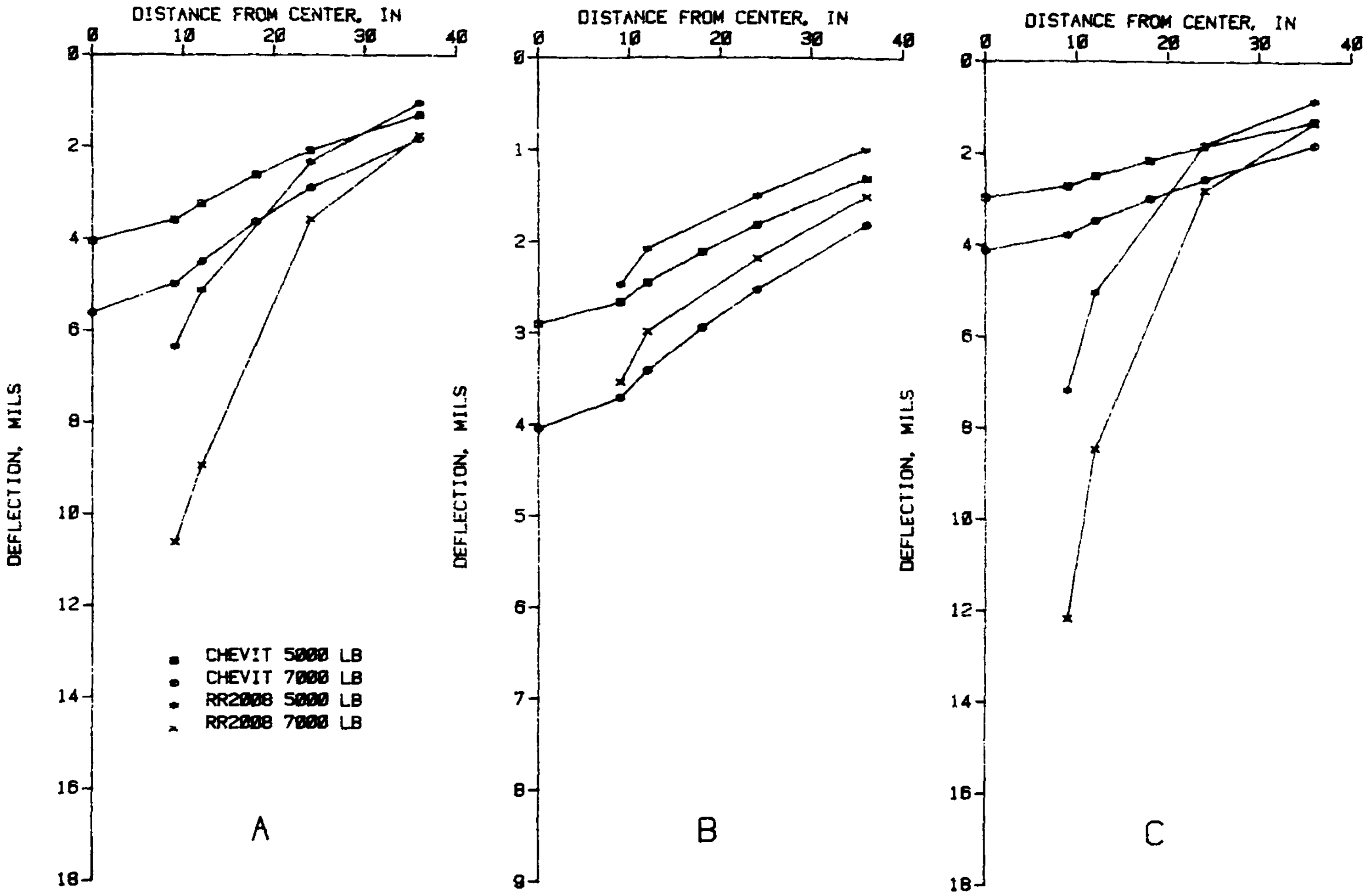


Figure 10. Predicted and measured basins on PTRF items A, B, and C (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 44.8 N)

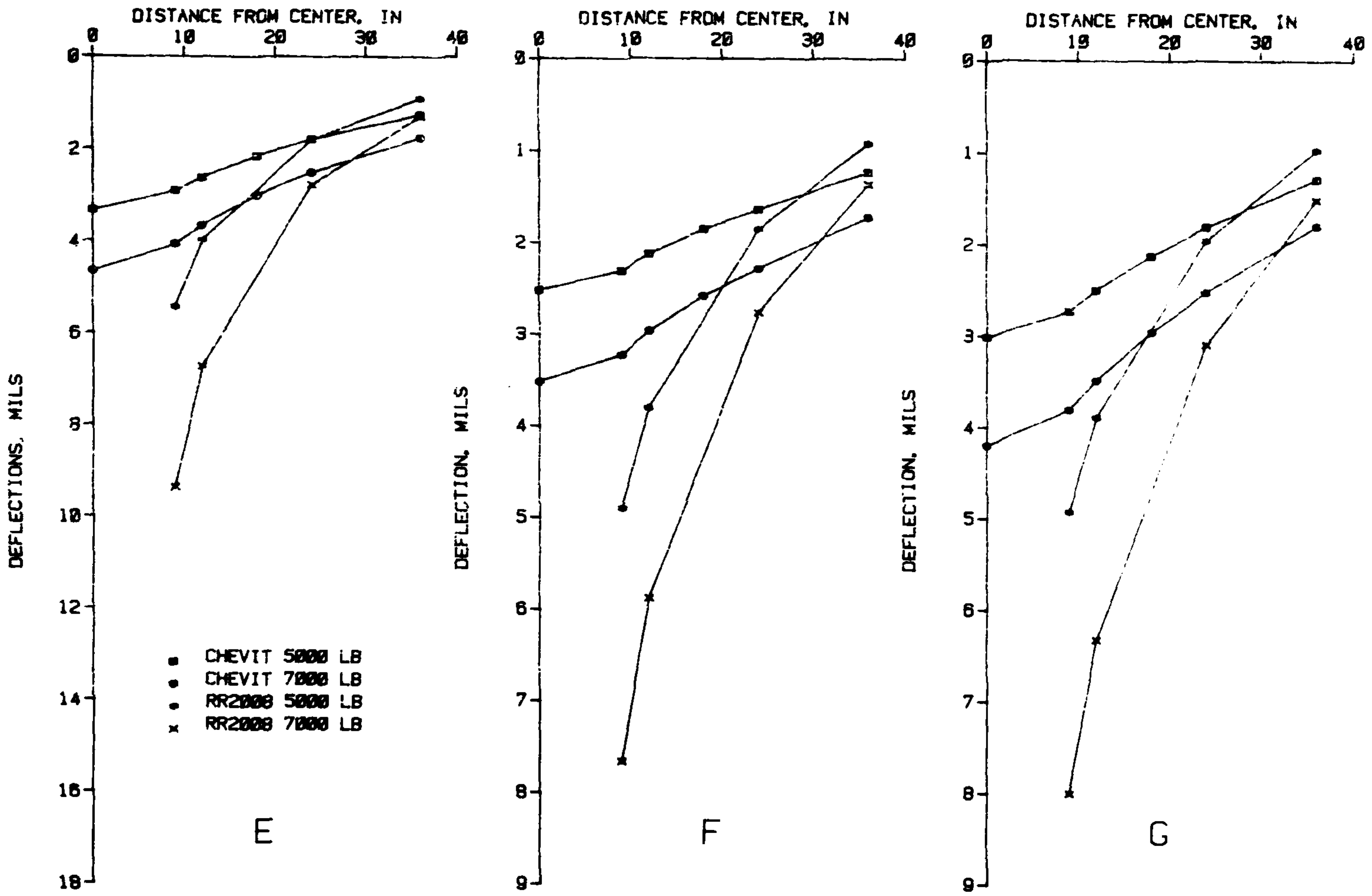


Figure 11. Predicted and measured basins on PTRF items E, F, and G
(1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

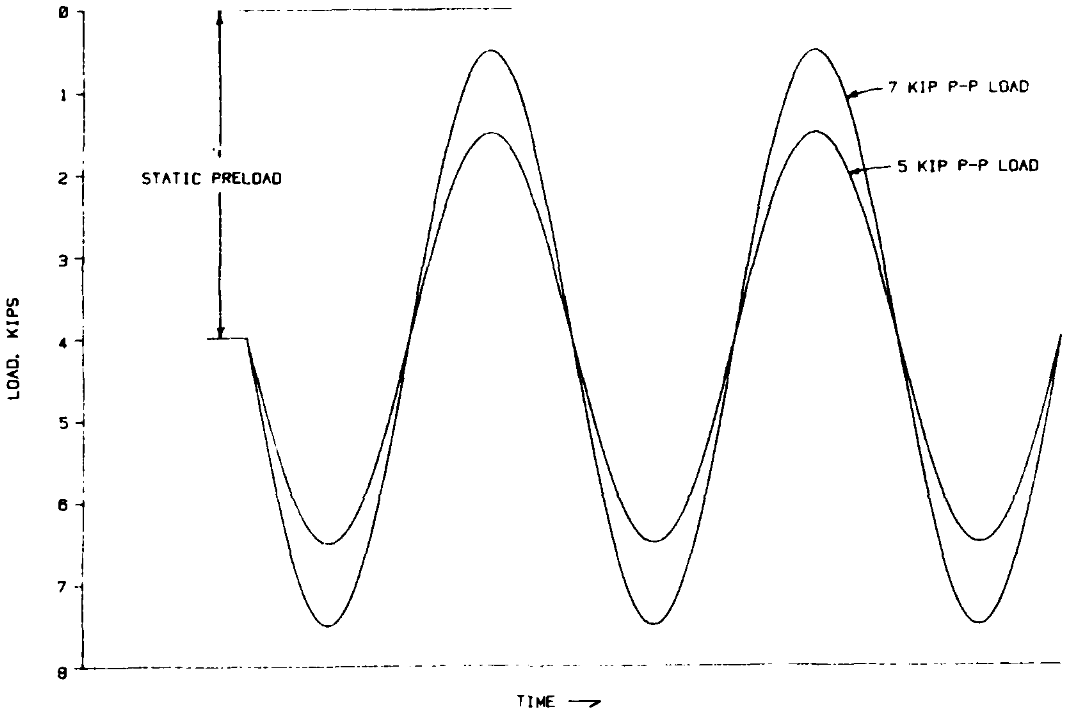


Figure 12. Load versus time history for 5000- and 7000-lb (5- and 7-kip) loads of the Model 2008 Road Rater (1 kip = 4.448 kN)

Table 3

Comparison of the Effects of Static Preload on PTRF Items 1A, 1B, and 2 Using the CHEVIT Program

Load lb	flections, mils, at Cited Distances, in.							
	0	9	12	18	24	36	48	60
				PTRF 1A				
6500	6.086	5.232	4.620	3.532	2.712	1.666	1.027	0.715
1500	1.567	1.349	1.194	0.911	0.692	0.408	0.239	0.161
Diff 5000	4.519	3.883	3.426	2.621	2.020	1.258	0.788	0.554
5000	4.797	4.125	3.643	2.782	2.130	1.294	0.790	0.546
Percent Difference	6.2	6.2	6.3	6.1	5.4	2.9	0.3	-1.4
7500	6.925	5.954	5.257	4.022	3.095	1.913	1.187	0.829
500	0.543	0.468	0.415	0.317	0.240	0.140	0.080	0.053
Diff 7000	6.382	5.486	4.842	3.705	2.855	1.773	1.107	0.776

(Continued)

Note: 1 lbf = 4.448 N; 1 in. = 2.54 cm.

Table 3 (Concluded)

Load lb	Deflections, mils, at Cited Distances, in.							
	0	9	12	18	24	36	48	60
7000	6.507	5.594	4.940	3.778	2.904	1.790	1.107	0.772
Percent Difference	2.0	2.0	2.0	2.0	1.7	1.0	0.0	-0.5
PTRF 1B								
6500	7.128	5.829	5.014	3.598	2.641	1.589	0.970	0.694
1500	1.849	1.511	1.299	0.922	0.660	0.372	0.217	0.153
Diff 5000	5.279	4.318	3.715	2.676	1.981	1.217	0.753	0.541
5000	5.614	4.588	3.944	2.820	2.057	1.221	0.739	0.528
Percent Difference	6.3	6.3	6.2	5.4	3.8	0.3	-1.9	-2.4
7500	8.120	6.644	5.718	4.113	3.030	1.837	1.127	0.806
500	0.646	0.529	0.455	0.323	0.229	0.126	0.072	0.050
Diff 7000	7.474	6.115	5.263	3.790	2.801	1.711	1.055	0.756
7000	7.625	6.237	5.366	3.856	2.835	1.713	1.048	0.750
Percent Difference	2.02	2.0	2.0	1.7	1.2	0.1	0.6	-0.8
PTRF 2								
6500	6.071	5.116	4.492	3.405	2.613	1.618	1.001	0.696
1500	1.471	1.238	1.086	0.817	0.620	0.374	0.226	0.157
Diff 5000	4.600	3.878	3.406	2.588	1.993	1.244	0.775	0.539
5000	4.706	3.963	3.477	2.630	2.013	1.240	0.764	0.532
Percent Difference	2.3	2.2	2.1	1.6	1.0	-0.3	-1.4	-1.3
7500	6.983	5.887	5.171	3.925	3.018	1.874	1.161	0.807
500	0.502	0.423	0.371	0.279	0.211	0.126	0.075	0.052
Diff 7000	6.481	5.464	4.800	3.646	2.807	1.748	1.086	0.755
7000	6.527	5.501	4.831	3.665	2.815	1.746	1.080	0.751
Percent Difference	0.7	0.7	0.6	0.52	0.3	-0.1	-0.6	-0.5

DETERMINATION OF LAYER MODULUS VALUES FROM BASIN DATA

DEVELOPMENT

The deflection basin produced by applying a load to the pavement with the Model 2008 Road Rater gives four input parameters to the system analysis that can be used to derive the strength parameters of the pavement layers. A program called CHEVDEF was developed to determine a set of modulus values that provide the best fit between a measured deflection basin and a computed deflection basin when given an initial estimate of the modulus values, a range of modulus values, and a set of measured deflections.

Consider the pavement system where:

a. The modulus is unknown for a number of layers (NL).

b. The deflection due to plate load is measured at a number of deflection (ND) locations.

c. ND is greater than NL .

The objective is to determine the set of E's that will minimize the error between the computed deflection Δ and the measured deflection RRD . To accomplish the objective, a relationship was developed for the deflection at a point j as a function of the unknown E's , i.e.,

$$\Delta j = f(E_1, E_2 \ldots E_{NL})$$

then the error at a position where the deflection was measured is

$$RRD_j - \Delta_j = RRD_j - f(E_1, E_2, \ldots E_{NL})$$

This expression is then squared and summed with respect to each measured deflection

$$\sum_{j=1}^{ND} ERROR^2 = \sum_{j=1}^{ND} \left[RRD_j - f_j(E_1 \ldots E_{NL}) \right]^2$$

To minimize the error with respect to an unknown E , the partial derivative of the error function is taken with respect to the E . By taking a derivative with respect to each unknown E , then a set of NL equations is obtained that can be solved giving the set of E's for the minimum error between the measured basin and the computed basin.

First, a set of E values is assumed and the deflection Δ_j^o is computed corresponding to the measured deflection RRD_j . Each unknown

E is varied individually and a new set of deflections is computed for each variation. Using the two computed deflections and the two values of each E , a function is determined for each deflection. For example, let

$$E\ell = \log_{10} E$$

Then the deflection at location 1 is given as a function of E_1 , i.e.,

$$\Delta_1 = A_{11} + S_{11}E\ell_1$$

where

$$S_{11} = \frac{\Delta_1^o - \Delta_1^1}{E\ell_1^o - E\ell_1^1}$$

$$A_{11} = \Delta_1^o - S_{11}E_1^o$$

$E\ell_1^o$ = $\log_{10}$ of first assumed value of E_1

$E\ell_1^1$ = $\log_{10}$ of E_1 after the variation

Δ_1^o = computed deflection at position 1 for E_1^o

Δ_1^1 = computed deflection at position 1 for E_1^1

Likewise, functions are determined for each deflection and each unknown E , resulting in $j = 1$ to ND and $i = 1$ to NL . Then

$$\Delta_j = A_{ji} + S_{ji}E\ell_i$$

To write an expression for Δ_j as a function of all E's , the following is used

$$\Delta_j = \Delta_j^o + (\text{changes in } \Delta_j^o \text{ due to changes in the E's})$$

Consider when the modulus of layer changes from E_1^o to E_1^1 , the change in Δ_j would be $S_{ji}(E\ell_1^1 - E\ell_1^o)$.

Thus

$$\Delta_j = \Delta_j^o + \sum_{i=1}^{NL} S_{ji}(E\ell_i - E\ell_i^o)$$

The value of Δ_j^o can be expressed in terms of any of the unknown E's, i.e., E_{NL}, as

$$\Delta_j^o = A_{jNL} + S_{jNL} E\ell_{NL}^o$$

The expression for Δ_j now becomes

$$\Delta_j = A_{jNL} + S_{jNL} E\ell_{NL}^o + \sum_{i=1}^{NL} S_{ji}(E\ell_i - E\ell_i^o)$$

The error squared for the jth position is $(RRD_j - \Delta_j)^2$ or

$$ERROR_j^2 = \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E\ell_{NL}^o + \sum_{i=1}^{NL} S_{ji}(E\ell_i - E\ell_i^o) \right] \right\}^2$$

The summation of the error for all readings is

$$\sum_{j=1}^{ND} ERROR_j^2 = \sum_{j=1}^{ND} \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E\ell_{NL}^o + \sum_{i-1}^{NL} S_{ji}(E\ell_i - E\ell_i^o) \right] \right\}^2$$

If a weight term W_j for each reading is to be applied, then the expression becomes

$$\sum_{j=1}^{ND} [W_j - (ERROR)]^2 = \sum_{j=1}^{ND} \left(W_j \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E\ell_{NL}^o + \sum_{i=1}^{NL} S_{ji}(E\ell_i - E\ell_i^o) \right] \right\} \right)^2$$

Taking the partial with respect to each E and setting the partial equal to zero, the following is obtained:

$$0 = \sum_{j=1}^{ND} S_{jk} W_j \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E\ell_{NL}^o + \sum_{i=1}^{NL} S_{ji}(E\ell_i - E\ell_i^o) \right] \right\}$$

If the equations derived are put in the form

$$[B]\ \{E\} = \{C\}$$

the $\{C\}$ terms are the constant part of the equation. For $k = 1$ to NL

$$C_k = \sum_{j=1}^{ND} S_{jk} W_j \left[RRD_j - \left(A_{jNL} + S_{jNL} E\ell_{NL}^o - \sum_{i-1}^{NL} S_{ji} E\ell_i^o \right) \right]$$

and the $[B]$ for $k = 1$ to NL and $i = 1$ to NL is

$$B_{ki} = \sum_{j=1}^{ND} S_{jk} W_j S_{ji}$$

If the weight term is chosen to be $W_j = \frac{1}{RRD_j}$, the result is the same as developing the equation from

$$ERROR_j = \frac{RRD_j - \Delta_j}{RRD_j}$$

which is a percent type error. The solution of the equation is the set of E's that minimizes the percent error. The efficiency of the procedure will depend on how well the functions represent the actual relationship between the computed deflection and the E's .

It appears that as long as the final E values are within the initial input limits, the $\Delta = f(\log_{10} E)$ is a good representation of the relationship.

A computer program named CHEVDEF, consisting of the procedure described above, was used in developing the pavement evaluation procedure reported herein. CHEVDEF uses the CHEVRON layered elastic program as a subroutine to compute surface deflections. A flowchart, input format, example input, example output, and a listing of CHEVDEF are presented in Appendix B.

The limitations of this approach are that the layered elastic theory assumes a uniform pressure applied to the surface of the pavement. With the Model 2008 Road Rater, the load is applied through a rigid circular plate with the center deflection measured on top of that plate. Therefore, a difference does exist in the measured center deflection and a deflection computed from layer elastic procedures at the center of the load area, as illustrated by Fossberg[12] in Figure 13. Note that the elastic layer solution and field data coincide at approximately three-fourths of the radius of the plate. In order to determine the optimum spacing for the deflection measurements, computations such as shown in Figures 14 and 15 were made with the CHEVDEF program for flexible and rigid pavements, respectively. Spacing distances of 0, 4.5, 6, and 9 inches were used for the computations. Varying these distances caused little change in the subgrade modulus for either the flexible or the rigid pavement. There was variation in the surface modulus on the flexible pavement. Based on the temperature-frequency relationship presented in Figure 3, the modulus of the asphalt layer should be 520,000 psi. Thus, from Figure 15, a distance between 4.5 and 6 in. appears to produce the best results.

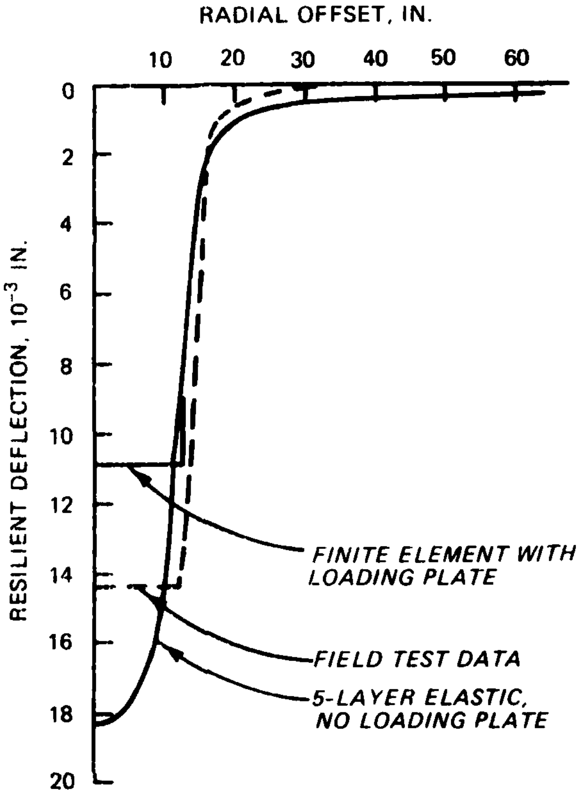


Figure 13. Patterns of resilient deflections under a 24-in.-diameter plate (plate pressure = 4 psi) directly on the subgrade (1 in. = 2.54 cm) (after Fossberg[12])

SENSITIVITY ANALYSIS

To evaluate the accuracy of the CHEVDEF, an analysis was made on a thin and a thick pavement section. The CHEVRON program was used to calculate deflections for the two pavement sections. These deflections were used as measured deflections for this analysis so that an error associated with field measurements would be eliminated. Tables 4 and 5 present the results. The modulus values listed as correct values in these tables were input to the CHEVRON program to give the deflections that were used as measured deflections in CHEVDEF. In the first case, the initial estimate for modulus was higher than the correct values. The initial estimate was lower than the correct values for the second

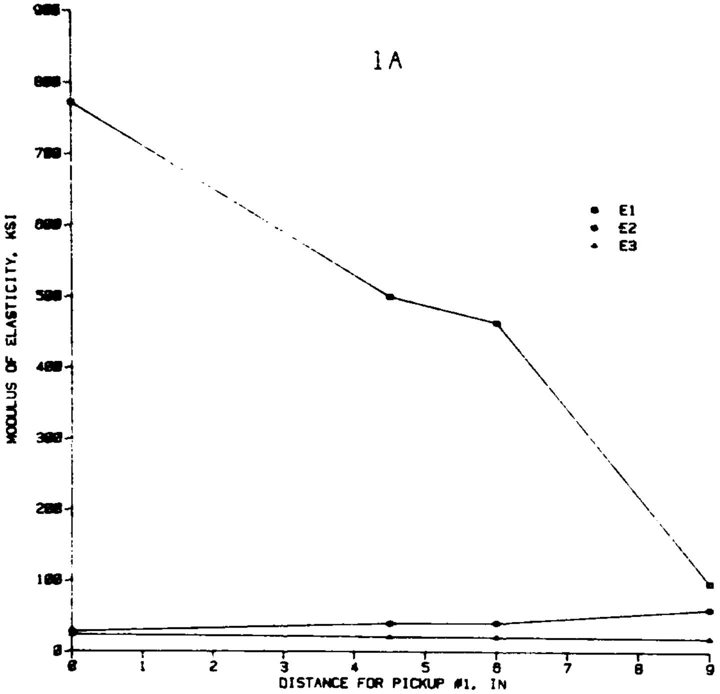


Figure 14. Effect of distance from center of rigid plate on predicted modulus for flexible pavement (1 ksi = 6.89 MPa; 1 in. = 2.54 cm)

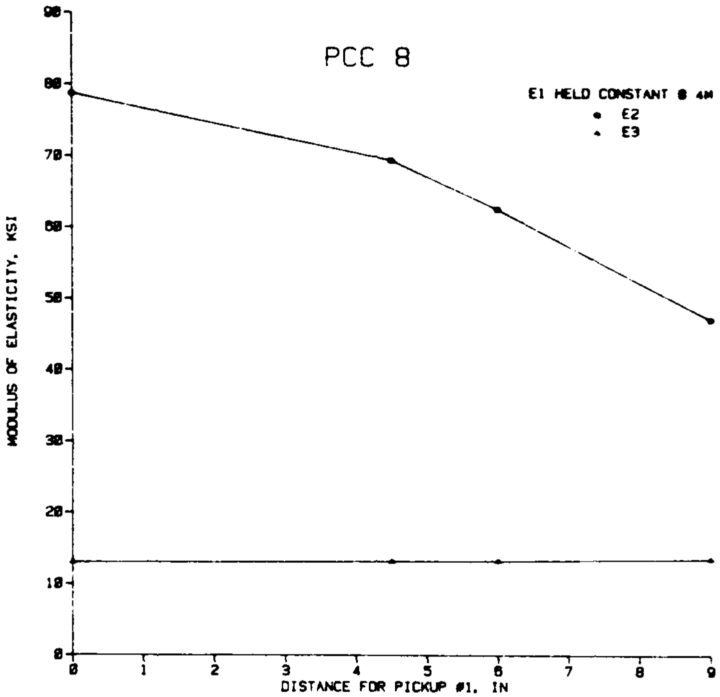


Figure 15. Effect of distance from center of rigid plate on predicted modulus for rigid pavement (1 ksi = 6.89 MPa; 1 in. = 2.54 cm)

Table 4

Reproducibility of the CHEVDEF Program for a Thin Section

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance from ¢ of Load, in.			
	E_1 1.5	E_2 4.0	E_3 8	E_4 226.5	Δ_1 4.5	Δ_2 12	Δ_3 24	Δ_4 36
First case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	450,000	800,000	100,000	30,000	5.1117	3.8035	2.3464	1.5035
Range (min-max)	(100,000-600,000)	(200,000-900,000)	(20,000-150,000)	(5,000-70,000)				
Final	156,192	371,545	47,638	14,900	10.6439	7.7864	4.7103	2.9842
Second case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	60,000	100,000	15,000	10,000	21.9558	14.2438	7.2535	4.2921
Range (min-max)	(50,000-300,000)	(50,000-500,000)	(10,000-80,000)	(5,000-30,000)				
Final	50,000	444,279	54,032	14,845	10.9201	7.7747	4.7400	3.0141
Third case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	100,000	600,000	35,000	25,000	8.2731	5.6602	2.9723	1.7357
Range (min-max)	(50,000-300,000)	(200,000-700,000)	(20,000-80,000)	(5,000-30,000)				
Final	90,830	509,630	48,784	15,114	10.5267	7.7027	4.6783	2.9597

Note: 1 psi = 703 kg/m^2; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

Table 5

Reproducibility of the CHEVDEF Program for a Thick Section

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance from ℄ of Load, in.			
	E_1 2.5	E_2 8	E_3 8	E_4 221.5	Δ_1 4.5	Δ_2 12	Δ_3 24	Δ_4 36
First case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	450,000	800,000	100,000	30,000	5.5603	4.3504	3.1429	2.2268
Range (min-max)	(100,000-600,000)	(200,000-900,000)	(20,000-150,000)	(5,000-70,000)				
Final	198,498	352.192	44,808	15,006	7.2798	5.734	4.1821	2.970
Second case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	60,000	100,000	15,000	10,000	15.5701	11.0651	7.0534	4.5442
Range (min-max)	(50,000-300,000)	(50,000-500,000)	(10,000-80,000)	(5,000-30,000)				
Final	196,507	345,207	47,571	14,950	7.2656	5.7153	4.1752	2.9727
Third case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	100,000	600,000	35,000	25,000	5.4674	4.0482	2.8051	1.8720
Range (min-max)	(50,000-300,000)	(200,000-700,000)	(20,000-80,000)	(5,000-30,000)				
Final	173,674	380,337	47,545	15,078	7.1869	5.6577	4.1483	2.9536

Note: 1 psi = 703 kg/m^2; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

case. In the third case, the initial estimate was alternated between low and high values. The program reasonably reproduced all modulus values for the thick section but varied from the correct values for the thin upper layers for the thin section. The values for the the two bottom layers were very close even for the thin section.

To determine the reproducibility for different spacings of deflections, the data for the thick section were selected. Table 6 lists the results of this analysis. No significant difference occurred due to the location of the deflection with respect to the final value of modulus for up to four layers.

Another check was made on a typical section with a stiff (stabilized) layer. Table 7 summarizes the results. Again the program produced a good approximation of the correct values for the four-layer system.

To determine the sensitivity of the CHEVDEF program to the Poisson's ratio of each layer, an analysis was made using the thick section. The Poisson's ratio was varied between 0.2 and 0.5 for each layer. Figure 16 shows the change in modulus values for these variations in the Poisson's ratio. There is little effect on the predicted modulus values when the Poisson's ratios for layer 2 and layer 3 are varied. The variations are large in layer 1 and layer 2 when the Poisson's ratios of layer 1 and layer 4 are varied. In all cases, there is little variation in the modulus of the lower layers.

A Poisson's ratio of 0.35 will be assigned to all layers above the subgrade, and a ratio of 0.4 will be assigned to the subgrade.

PREDICTION OF LAYER MODULUS VALUES

The CHEVDEF program was used to predict modulus values for the 15 PTRF test items. Table 8 presents the results. Layer 1 includes all the AC material, and the modulus value for this layer was taken from the 16-Hz relationship in Figure 3. The pavement temperature was computed from the surface temperature plus the previous five-day mean.[13]

Basins predicted from the program were not plotted against the measured basins, but the small differences can be seen in the column entitled "Absolute Sum of Differences in Deflections." In each case, this is the sum of the differences in four deflections.

Table 6

Reproducibility of CHEVDEF Program for a Thick Section with Variable Deflection Distances

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflection, mils			
	E_1	E_2	E_3	E_4	Δ_1	Δ_2	Δ_3	Δ_4
	1.5	4	8	226.5				
					Distance, in.			
First case:					0	9	18	30
Correct	200,000	350,000	45,000	15,000	7.488	6.504	4.892	3.535
Assumed	300,000	400,000	60,000	20,000				
Range (min-max)	(100,000-400,000)	(200,000-500,000)	(30,000-70,000)	(10,000-30,000)				
Final	175,264	367,258	45,721	15,021	7.4880	6.5039	4.8918	3.5349
Second case:					4.5	12	24	36
Correct	200,000	350,000	45,000	15,000	7.280	5.734	4.182	2.970
Assumed	300,000	400,000	60,000	20,000				
Range (min-max)	(100,000-400,000)	(200,000-500,000)	(30,000-70,000)	(10,000-30,000)				
Final	198,498	352,192	44,808	15,006	7.2798	5.7340	4.1821	2.9700
Third case:					9	18	30	42
Correct	200,000	350,000	45,000	15,000	6.504	4.892	3.535	2.497
Assumed	300,000	400,000	60,000	20,000				
Range (min-max)	(100,000-400,000)	(200,000-500,000)	(30,000-70,000)	(10,000-30,000)				
Final	197,002	357,639	45,586	15,007	6.5033	4.8913	3.5347	2.4969

Note: 1 psi = 703 kg/m^2; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

Table 7

Reproducibility of the CHEVDEF Program for a Section with a Stiff Layer

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance, in.			
	E_1 5.0	E_2 8.0	E_3 8.0	E_4 219.0	Δ_1 4.5	Δ_2 12	Δ_3 24	Δ_4 36
Correct	300,000	1,000,000	45,000	10,000	6.371	5.437	4.698	3.821
Assumed	200,000	1,500,000	60,000	15,000	4.9629	4.0108	3.3981	2.6983
Range (min-max)	(100,000-400,000)	(500,000-2,000,000)	(30,000-700,000)	(5,000-20,000)				
Final	284,249	1,148,323	33,730	10,207	6.3562	5.4204	4.6799	3.8040

Note: 1 psi = 703 kg/m^2; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

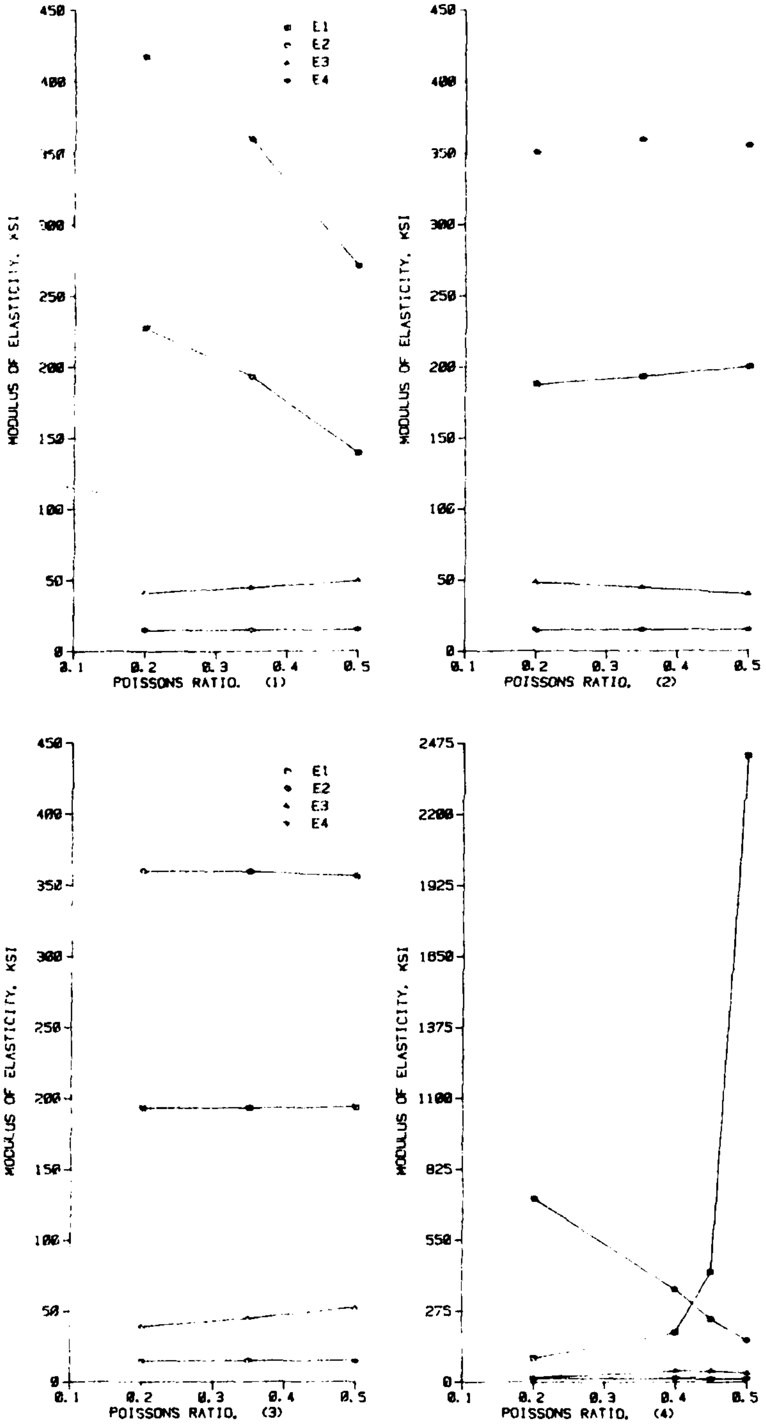


Figure 16. Effect of varying Poisson's ratios (ν_1, ν_2, ν_3, and ν_4) on predicted modulus values (1 ksi = 6.89 MPa)

Table 8

Predicted Modulus Values for PTRF Items from CHEVDEF

Item	Load lb	Predicted Modulus Values, psi E_1	E_2	E_3	E_4	No. of Iterations	Absolute Sum of Differences in Deflections, %	Subgrade Stress, psi σ_V	$\sigma_T = \sigma_R$	σ_D	Subbase Bulk Stress, psi	$E_s = S\sigma_D + I$ Slope S	Inter I	Subgrade E for PAVEVAL psi
1A	5000	345,255	60,446	23,387	--	2	13.3461	1.477	-0.03685	1.52	10.67			
	7000	500,060	40,304	21,130	--	1	8.6555	2.019	-0.01701	2.04	11.09	- 4,334	29,954	8,322
1B	5000	468,548	22,040	35,733	--	2	2.049	2.573	0.2828	2.29	7.363			
	7000	396,018	21,750	30,523	--	2	3.442	3.630	0.3297	3.30	10.71	- 5,158	47,546	11,621
2	5000	437,218	15,681	47,717	--	2	8.0057	3.381	0.7890	2.59	7.137			
	7000	380,000	11,567	44,445	--	3	14.7086	6.411	1.721	4.69	9.853	- 1,560	51,759	26,739
3	5000	215,000	79,289	6,800	35,254	3	13.9810	3.589	0.8177	2.77	7.201			
	7000	215,000	79,289	5,492	28,827	3	10.9942	4.641	1.121	3.52	9.317	- 8,584	59,043	9,600
4	5000	205,000	3,600,000	13,879	30,667	2	9.5409	1.126	0.3645	0.76	2.325			
	7000	205,000	3,600,000	16,683	25,391	1	8.0600	1.503	0.4150	1.09	3.051	-16,159	42,972	4,015
5	5000	231,000	250,000	8,783	38,803	2	8.3136	2.837	0.7802	2.06	5.819			
	7000	231,000	174,367	8,405	35,001	3	9.5814	4.237	1.050	3.19	8.619	- 3,364	45,722	15,118
6	5000	475,000	44,658	29,920	--	2	14.1059	2.316	0.08991	2.23	4.119			
	7000	475,000	28,149	29,388	--	2	5.5151	3.203	0.2996	2.90	6.066	- 785	31,669	21,525
7	5000	447,694	70,887	32,441	--	2	3.1929	2.698	0.02184	2.68	5.018			
	7000	447,694	67,898	29,819	--	3	4.8529	3.651	0.02804	3.62	6.674	- 2,769	39,852	14,973
8	5000	249,007	12,142	35,889	--	3	15.4879	4.049	0.8642	3.18	8.680			
	7000	196,830	12,366	28,814	--	2	4.3656	5.867	1.033	4.83	12.63	- 4,290	49,552	13,565
A	5000	341,000	500,000	5,653	38,916	2	9.3311	3.718	1.347	2.37	5.120			
	7000	341,000	348,856	4,522	34,615	3	25.7044	5.186	1.986	3.30	11.22	- 4,630	49,893	13,217
B	5000	380,000	3,201,569	20,717	36,852	2	6.4854	1.900	0.5103	1.39	4.074			
	7000	380,000	3,201,469	20,717	34,405	2	1.0477	2.599	0.6797	1.92	5.565	- 4,620	43,273	11,471
C	5000	432,000	75,750	7,723	39,631	3	16.9104	4.338	0.9301	3.41	8.809			
	7000	432,000	51,233	6,834	34,526	4	19.5240	6.370	1.269	5.10	12.86	- 3,015	49,906	17,766
E	5000	430,000	69,430	8,043	44,664	1	7.6956	3.037	0.6598	2.38	5.868			
	7000	430,000	41,887	7,251	40,723	3	7.1449	4.598	0.929	3.67	8.816	- 3,055	51,935	18,332
F	5000	535,000	61,136	7,933	46,135	3	7.0849	2.838	0.6791	2.16	5.466			
	7000	535,000	32,605	9,310	40,490	1	9.7553	4.307	0.8374	3.47	8.208	- 4,307	55,433	15,466
G	5000	628,000	98,443	7,204	44,071	2	4.9405	2.908	0.8203	2.09	5.757			
	7000	628,000	49,436	6,665	36,733	2	9.9899	4.183	1.098	3.09	8.220	- 7,358	59,432	17,976
													Mean =	14,501
													Standard Deviation =	5,734

Note: 1 lbf = 4.448 N; 1 psi = 703 kg/m^2.

The stress produced in the subgrade by the Model 2008 Road Rater may not be the stress associated with the design aircraft load. To account for this, two loads were analyzed (5000 and 7000 lb). The modulus values and stresses (vertical, longitudinal, and radial) at the top of the subgrade were calculated for each load level. With these values, a relationship between the modulus and the deviator stress can be developed for stress-dependent subgrades. Table 8 also shows the slope of the line and the intercept, as well as the bulk stress at the top of the subbase layer. There appears to be no relationship to the laboratory results for these values. The values of E for the granular layer are values that satisfy the model deflection basin. The granular material without a binder has very few load transfer properties through bending. Therefore, the model predicted lower modulus values. Associated with the low modulus value is a high vertical strain in that layer, which is considered a problem in using the layered elastic theory to model granular materials.

DETERMINATION OF SUBGRADE MODULUS FOR EVALUATION

Results from the CHEVDEF program give the relationship for the deviator stress and the modulus for the subgrade materials in the form

$$E = S\sigma_D + I$$

where

E = subgrade modulus
S = slope
σ_D = deviator stress
I = intercept

It is known from Hooke's Law and by definition for resilient modulus that

$$E = \frac{\sigma_D}{\varepsilon}$$

where ε represents the strain. By substituting and rearranging

$$E = SE\varepsilon + I$$

or

$$E = \frac{I}{1 - S\varepsilon}$$

If a limiting vertical compressive strain is selected, the modulus of the subgrade can be calculated. For comparisons used in this study, a value of 0.0006 in./in. was selected. This value was taken from an average line drawn on Figure 17 and represents 500,000 repetitions or 25,000 arrival/departures per year for 20 years. The equation for the average line is given as

$$\varepsilon_v = AN^B$$

where

ε_v = limiting vertical compressive strain in subgrade, in./in.
A = 0.0063548
N = number of strain repetitions
B = -0.17985

The modulus values in Table 9 associated with that strain level will be used for the evaluation of these pavements.

COMPARISON OF SUBGRADE MODULUS VALUES

The design modulus can also be computed from laboratory resilient modulus test results as outlined in Appendix A. The best-fit line for deviator stresses between 5 and 12 psi was calculated and then presented in Table 9. A comparison of the mean subgrade modulus values from the CHEVDEF program analysis (14,201 psi) to the laboratory results (12,864 psi) seems very reasonable.

Another comparison was made to the subgrade strength parameters derived from the DSM method reported by Green and Hall.[2] The PTRF facility was tested with the WES 16-kip vibrator at the same time that testing was conducted with the Model 2008 Road Rater. Table 10 summarizes results of the DSM evaluation. The subgrade strength factor is the equivalent of the design CBR for the subgrade. The factor is calculated as the CBR required to support a single-wheel load with a 254-sq-in. contact area for 1200 annual departures. The load on the wheel is determined by a correlation with the measured DSM. The relationship of 1500 times CBR was used to compare the design modulus values for the DSM method and for the layered elastic procedure (Figure 18). Except for two items (PTRF items 4 and B) that had very low deflections and high DSM's due to stabilized layers, subgrade strength design parameters approximate each other.

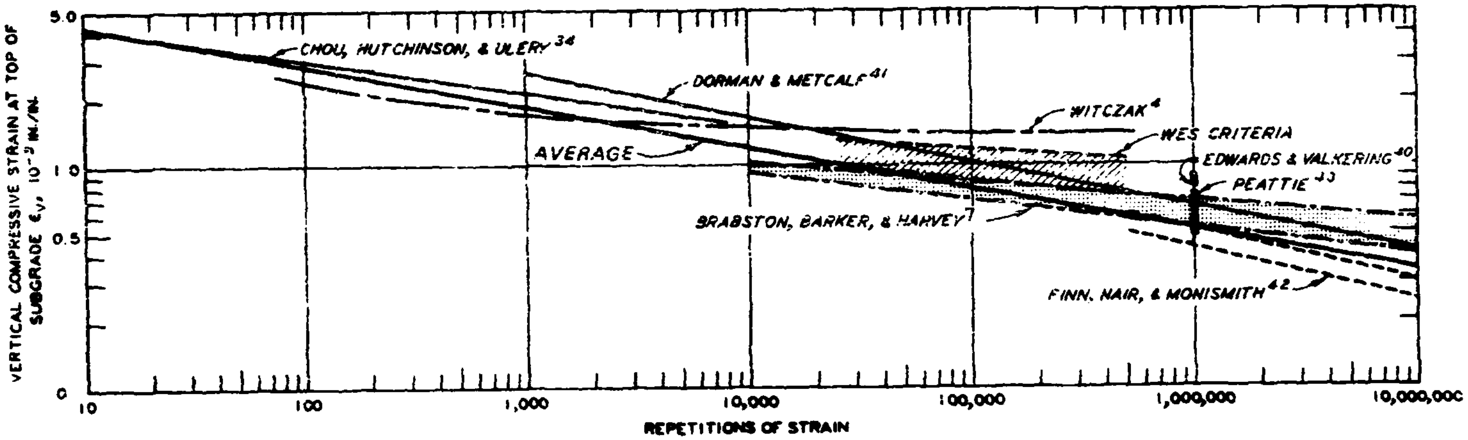


Figure 17. Comparison of subgrade strain criteria (1 in. = 2.54 cm) (after Barker and Brabston[14])

Table 9

Deviator Stress - Resilient Modulus Relationships from Laboratory Tests

Sample No.	Type Sample	Slope S	Intercept I	Design E* psi
I-1	Remolded	-1279	18,428	10,424
I-2	Remolded	-1052	15,632	9,585
II-1	Undisturbed	-1181	20,811	12,182
II-2	Undisturbed	- 932	22,581	14,484
III-1	Remolded	-3342	45,998	15,305
III-2	Remolded	-1049	15,089	9,261
III-3	Undisturbed	-1773	38,808	18,804
			Mean =	12,864
			Standard Deviation =	3,512

Note: 1 psi = 703 kg/m^2.

* Based on strain level of 0.0006 in./in.

Table 10

DSM Evaluation of the PTRF

PTRF Item*	Temperature Corrected DSM kips/in.	Subgrade Strength Factor	Allowable Gross Aircraft Load, kips 254 sq-in. Single Wheel**	Allowable Gross Aircraft Load, kips 127 sq-in. Single Wheel†
1A	1210	6.95	11.3	86.8
1B	1008	9.29	92.7	79.9
2	1331	18.97	122.4	103.8
3	813	11.79	74.7	58.3
4	2286	26.4	210.3	181.9
5	863	9.58	79.4	61.6
6	1542	15.9	141.9	116.8
7	1254	15.2	115.4	96.9
8	657	9.05	60.4	45.5
A	605	11.1	55.7	40.2
B	1634	25.6	150.3	131.9
C	661	8.85	60.8	45.5
E	708	6.49	65.1	48.2
F	859	9.5	79.0	61.3
G	689	9.15	63.3	47.5

Note: 1 kip = 4.448 kN; 1 kip/in. = 1.75 kN/cm; 1 sq in. = 6.45 sq cm.

* See Table 2 for a description of these pavements.

** 1,200 annual departures, 20-year life.

† 25,000 annual departures, 20-year life.

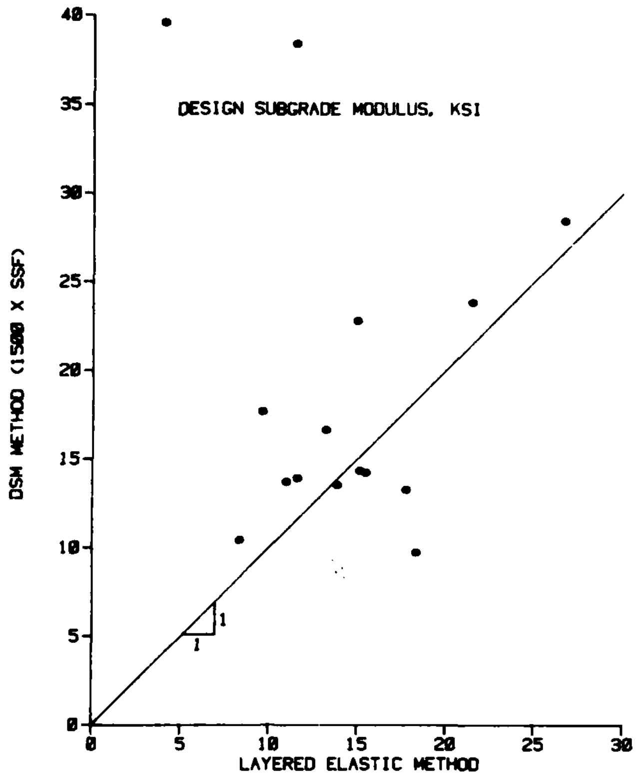


Figure 18. Comparison of subgrade modulus by the DSM and layer elastic method (1 ksi = 6.89 MPa)

EVALUATION OF ALLOWABLE AIRCRAFT LOADS

For the evaluation of the allowable aircraft loads, the PAVEVAL computer program reported by Weiss[3] was used. For flexible pavements, this program calculates the vertical compressive strain at the top of the subgrade and the tensile strain at the bottom of the AC layer. These strains are compared to the limiting strain criteria reported by Barker and Brabston.[14] For rigid pavements, the limiting tensile stress in terms of the number of load (stress) repetitions from Parker et al.[15] is considered as

$$\sigma_{RL} = \frac{R}{A + B \log (\text{cov})}$$

where

σ_{RL} = limiting value of tensile stress, psi
R = flexural strength, psi
A = 0.58901

B = 0.35486

cov = number of coverages (The number of coverages is determined by dividing the number of aircraft departures by the departure-to-coverage ratio. The ratio used for single-wheel gears was 7.94 and for dual-wheel gears was 5.2.)

Example inputs and outputs for evaluation of light aircraft allowable loads on rigid and flexible pavements are given in Appendix C. A comparison of the allowable gross loads for the PTRF items was made between the DSM method and the layered elastic procedure (Figure 19). For comparison purposes, the design loads were calculated for a single-wheel aircraft with 127-sq-in. contact area and 25,000 annual departures.

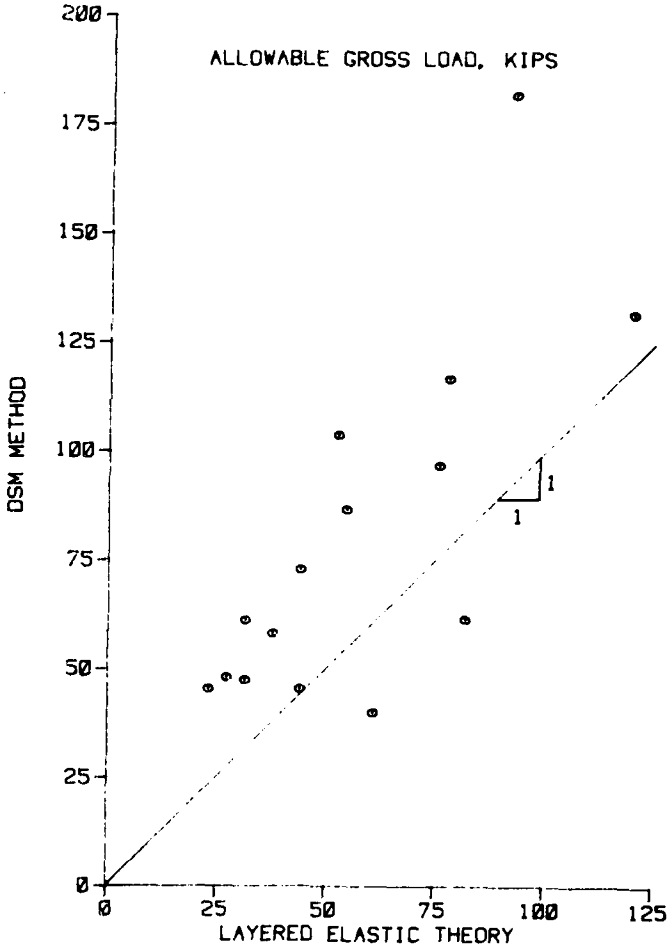


Figure 19. Comparison of allowable gross aircraft loads from the DSM and layered elastic methods (1 kip = 4.448 kN)

For the layered elastic evaluation, the modulus of the AC was selected as 770,000 psi, which corresponds to the 70°F temperature in Figure 3. The modulus of the subbase and base course layers (E2 in three-layer items, and E2 and E3 in four-layer items) were taken from the 7000-lb load in Table 8.

The allowable loads calculated from the DSM method are generally higher than those calculated using PAVEVAL. The controlling strain is shown in Table 11 for each of the PTRF items. The lower allowable loads for the layered elastic evaluations are probably due to the tensile strain controlling and being based on the initiation of a crack in the bottom of the AC rather than the crack propagating through the AC to the surface as was the case in the DSM evaluation (CBR Design System).

Table 11

Allowable Gross Aircraft Loads from PAVEVAL

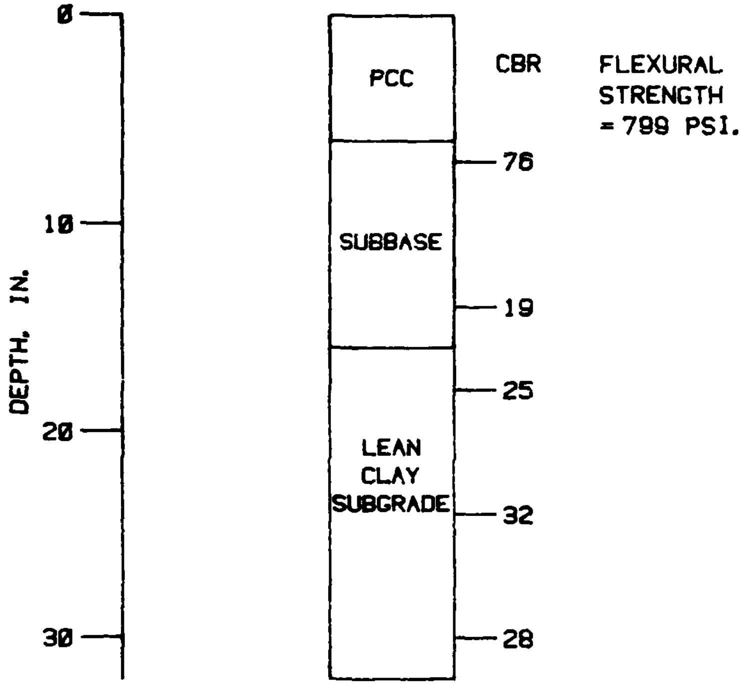
PTRF Item	Allowable Gross Aircraft Load kips	Controlling Strain Vertical Subgrade	Controlling Strain Tensile AC
1A	54.7		X
1B	44.2		X
2	52.6		X
3	37.9		X
4	92.6	X	
5	82.1	X	
6	77.9		X
7	75.8		X
8	44.2		X
A	61.1	X	
B	120.0	X	
C	23.2		X
E	27.4		X
F	31.6		X
G	31.6		X

Note: 1 kip = 4.448 kN.

A limited amount of testing was conducted on rigid pavements to verify the applicability of this procedure. Tests with the Model 2008 Road Rater were conducted on a portland cement concrete (PCC) road with the pavement structure as shown in Figure 20. Laboratory resilient modulus tests were not conducted on the subbase but were conducted on the subgrade material (Figure 21).

Table 12 presents the CHEVDEF program results for this rigid pavement. The subgrade modulus selected for evaluation for rigid pavements is the modulus that is associated with a 5-psi deviator stress[15] and is calculated directly from the slope and intercept derived from the deviator stress-modulus relationship for the 5000- and 7000-lb loads.

Also shown in Table 12 is the modulus for 5-psi deviator stress from the laboratory resilient modulus test. CBR tests were taken to depths of 30 in. The sample taken from the 30- to 45-in. depth indicated a higher strength material (Figure 20). Therefore, the predicted subgrade modulus seems to be a reasonable estimate of the subgrade strength.



NOTE: SAMPLE FOR RESILIENT MODULUS TESTING WAS TAKEN FROM DEPTH 30 TO 45 INCHES.

Figure 20. Pavement structure and test results on PCC pavement (1 in. = 2.54 cm; 1 psi = 703 kg/m^2)

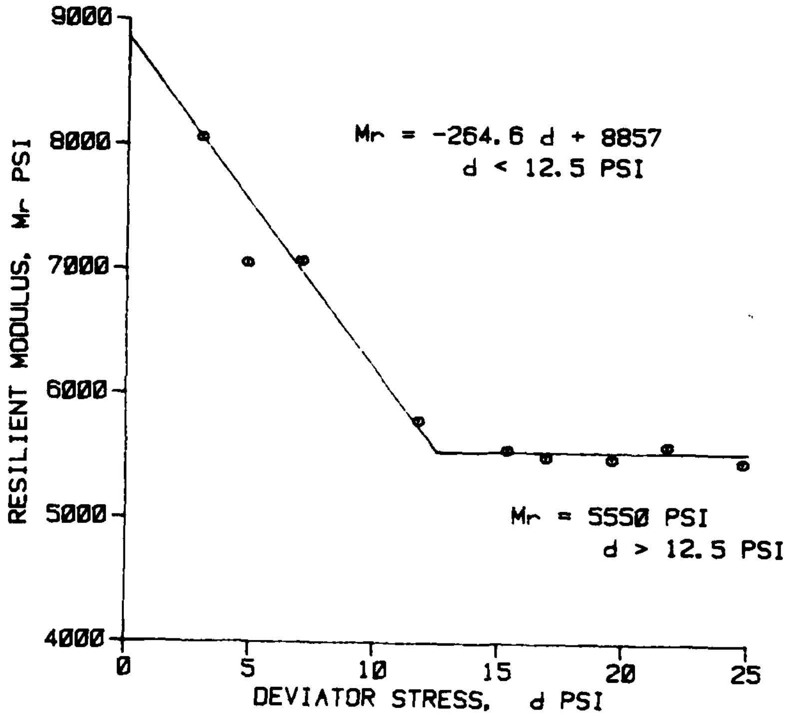


Figure 21. Results of resilient modulus tests on the PCC pavement subgrade material (1 psi = 703 kg/m^2)

Table 12

Predicted Modulus for PCC Pavement

Load lb	Predicted Modulus Values, psi			Abs Sum of % Diff	Subgrade			Subbase θ (bulk)	$E_s = S\sigma_D + I$		Subgrade E for PAVEVAL psi	Subgrade E from Lab Test psi
	E_1	E_2	E_3		σ_V	$\sigma_T = \sigma_N$	σ_D		Slope S	Inter I		
5000	4,000,000	81,873	13,145	11.1487	1.195	0.07143	1.1236	2.665				
7000	4,000,000	78,787	13,082	6.6225	1.678	0.1022	1.5758	3.721	-139	13,302	12,607	7,530

Note: 1 lbf = 4.448 N; 1 psi = 703 kg/m^2.

NONDESTRUCTIVE EVALUATION PROCEDURE

GENERAL

The procedure outlined in this section is for both rigid and flexible pavements and is based on a layered elastic model that characterized multilayered pavement systems. The layer strength parameters are computed from field in situ measurements. The strength parameters will be input into an evaluation program that is designed to handle multiwheel aircraft at varying traffic levels. The output will be computed as the allowable load for a 20-year design life pavement. The evaluation will be valid for conditions existing at the time of test and will not account for changes due to such factors as frost action or moisture in the subgrade. These factors should be accounted for through conventional procedures.

NONDESTRUCTIVE TESTING EQUIPMENT

The need for a device with variable loading characteristics is required to describe the nonlinear characteristics of the subgrade material. Laboratory resilient modulus tests would be required to describe these nonlinear characteristics when the description cannot be derived from the NDT data.

The NDT device must output a minimum of three deflections of which one is measured near the applied load and the others are spaced to a distance of at least 36 in. from the applied load. The number of deflection measurements limits the number of variable modulus layers that can be analyzed with this procedure. It is recommended that the magnitude of the first deflection (that deflection measured nearest to the applied load) be at least 0.2 mil.

DATA COLLECTION

PAVEMENT INFORMATION

Before evaluating a light aircraft pavement, information as to pavement types, layer thicknesses, and layer types must be derived from construction records or from destructive tests (cores or test pits). This information is required for the evaluation of allowable load as well as for the determination of NDT locations. If test pits or cores are required, these tests should be performed after the NDT. Areas of high and low deflections should be included with areas selected through a conventional sampling procedure to identify the causes of these unique NDT responses. Rigid pavement cores or beams should be tested for flexural strength.

The pavement condition should be surveyed to determine the areas and types of distress. It is not within the scope of this procedure to outline a detailed condition analysis. Since material properties are affected by water, frost, and primarily environmental conditions, it may be necessary to reduce the strength parameter for anticipated freeze/thaw conditions, alligator cracking in flexible pavements, and the presence of joints and cracks in rigid pavements.

TEMPERATURE DATA

Temperature data are required for AC pavements to evaluate the pavement properties at the time of testing and the ability of the pavement system to support future operations. The pavement temperature during the time of testing is determined at the mid-depth of the AC layer, the pavement surface, ambient temperature, and the previous five-day mean air temperature from Figure 22.[13] The pavement surface temperature should be measured at one-hour intervals during the period of testing. The mean air temperature can be obtained from the nearest office of the National Oceanographic and Atmospheric Administration.

To evaluate the pavement system for future operations, the average daily maximum temperature and average daily mean temperature is needed for the hottest months and the spring thaw months. These data can also be obtained from the nearest office of the National Oceanographic and Atmospheric Administration.

NDT TEST DATA

NDT should be conducted at 100-ft intervals alternating to either side of the center line in the wheelpaths on flexible pavements. Rigid pavement tests should be conducted in the slab center also alternating to either side of the feature center line. A minimum of five tests should be conducted in each pavement type. Parking aprons should be

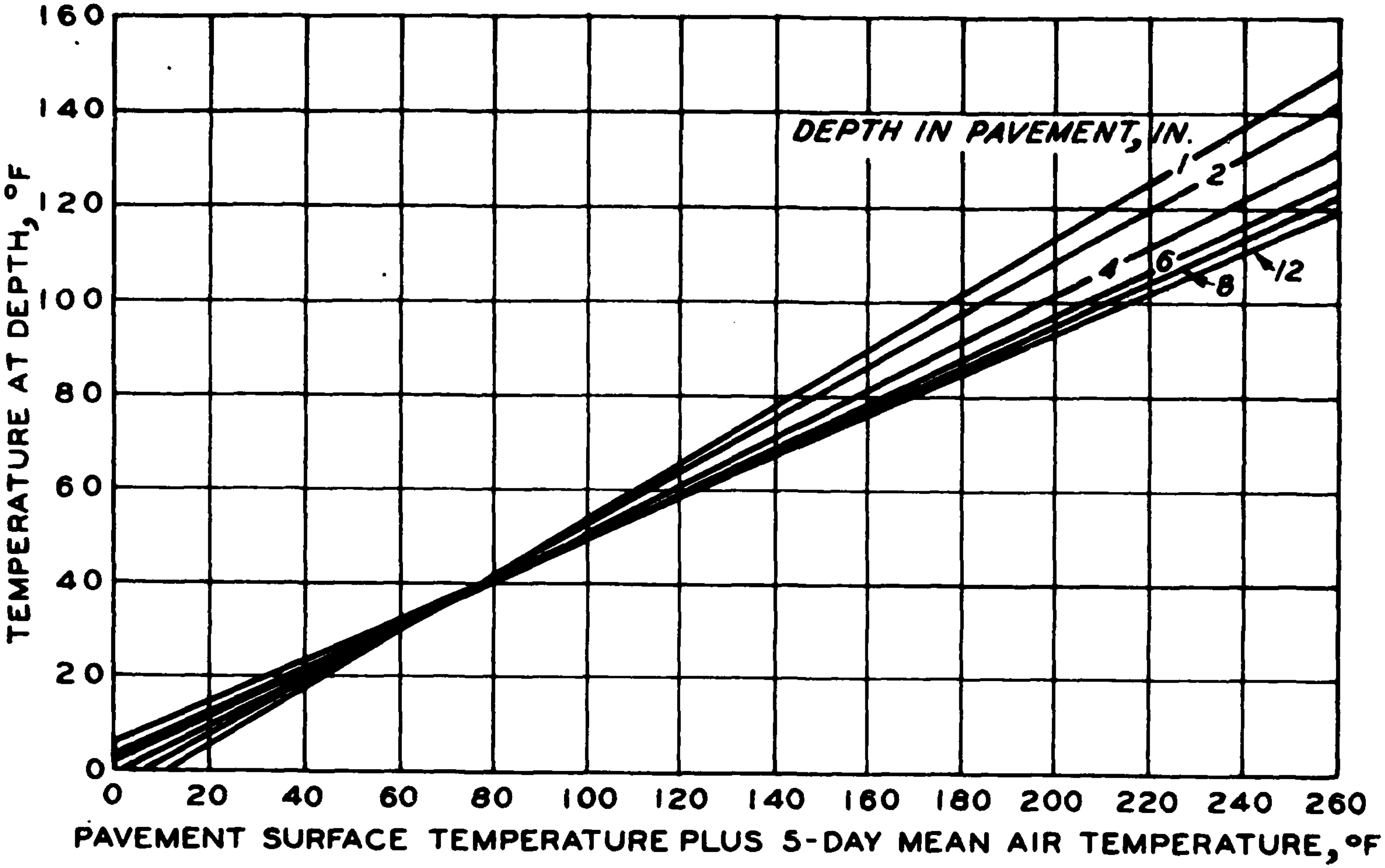


Figure 22. Prediction of flexible pavement temperatures (1°F = -17°C)

tested on a 200-ft grid system. Testing should not be conducted when the pavement or subgrade is frozen.

The NDT device should be operated at the frequency that produces the best signal response. For the Model 2008 Road Rater, this frequency is 15 Hz. Deflection basin data should be collected at the maximum force output of the device and at a force level of 50 to 75 percent of the maximum force output.

DETERMINATION OF LAYER MODULUS VALUES

The CHEVDEF program provides a tool with which the modulus values of up to four layers can be predicted. The CHEVDEF program input guide, typical input, and program listing are furnished in Appendix B. Sensitivity studies presented earlier in this report showed that the moduli of the subgrade and other lower layers in the pavement system reproduce well even when the surface moduli may differ. Also since the model assumes a uniform pressure and the Model 2008 Road Rater applies a rigid plate to the pavement, it is recommended that the modulus values of the surface layer be assigned as described below.

For flexible pavements, the modulus of the AC should be determined from Figure 3. The pavement temperature can be computed from the surface temperature plus the previous five-day mean air temperature (Figure 22). The depth should be the midpoint of the AC thickness.

Table 13 gives approximate ranges for the modulus of the pavement materials. These ranges represent very broad limits that should be compressed for the CHEVDEF program. For example, if a pavement with a cement-stabilized base is evaluated and the traffic history indicates very little heavy traffic has been applied, a range for the stabilized base should be selected between 600,000 and 1,500,000 psi.

NDT results should be analyzed by plotting the number one sensor deflection versus the distance along the feature. Pavement areas should be divided according to pavement types and pavement deflections. For each area, each deflection of the basin should be averaged to determine the mean deflection basin.

$$\frac{\Sigma D_1}{n} = \overline{D_1} \; ; \quad \frac{\Sigma D_2}{n} = \overline{D_2} \; ; \text{ etc.}$$

where

D_1 = deflection from number one sensor
n = number of tests in particular items
$\overline{D}$ = deflection to be used for evaluation

The mean deflection values for each pavement area should be input to CHEVDEF in mils.

Table 13

Typical Ranges for Modulus Estimates and Poisson's Ratio Values for Pavement Layers

Material	Range of Modulus 10^3 psi	Assigned Value of Poisson's Ratio
*AC	100 - 1000	0.35
PCC	4000 - 6000	0.15
Untreated base	2 - 160	0.35
Treated base	8 - 2000	0.35
Subgrade	2 - 37	0.4

Note: 1 psi = 703 kg/m^2.

* Temperature- and frequency-dependent.

In analyzing the results from the CHEVDEF program, it is important to check the predicted modulus for a layer against the limit. If the modulus does hit a limit, the program should be rerun modifying the limits to include the predicted E disregarding boundary conditions (see Appendix B, Example Output).

The highest load should be evaluated first with the CHEVDEF. The values for the modulus for the upper layers obtained from this run may be used for constant values when running the lower load to determine the relationship of stress versus modulus for the subgrade. For example, if the pavement contains three layers, consisting of AC, granular base, and subgrade, the modulus for the AC and granular layer as determined from the initial run of the high load should be held constant at the values for the run at the lower load.

Once the modulus values and deviator stress are obtained, the following equations are used to describe the nonlinearity of the subgrade:

$$S = \frac{E_1 - E_2}{\sigma_{D7} - \sigma_{D5}}$$

and

$$I = E_1 - S\sigma_{D7}$$

where

S = slope

E_1 = predicted modulus for high load (7000 lb for 2008 Road Rater)

E_2 = predicted modulus for low load (5000 lb for 2008 Road Rater)

σ_{D7} = deviator stress (vertical - radial stress) for 7000-lb load

σ_{D5} = deviator stress (vertical - radial stress) for 5000-lb load

I = intercept

After determining the S and I for the equation above, calculate the limiting strain for AC pavement from Figure 17 based on the design life of the pavement, and compute the design subgrade modulus from the equation given below:

$$E = \frac{I}{1 - S\varepsilon}$$

where

E = design subgrade modulus, psi

ε = limiting strain

For rigid pavements, the design subgrade modulus will be selected at a deviator stress of 5 psi, or

$$E = 5S + I$$

DETERMINATION OF ALLOWABLE AIRCRAFT LOADS

The PAVEVAL program presented by Weiss[3] will be used to predict allowable aircraft loads. Example inputs for both rigid and flexible pavements are shown in Appendix C. Aircraft characteristics[16] for light aircraft pavements are:

Type	Gross Max/Load kips	Departure to Coverage Ratio	Contact Area sq in.	Wheel Spacing, in.
Single	20	7.94	127	--
Dual	30	5.2	75	18

Note: 1 kip = 4.448 kN; 1 sq in. = 6.45 sq cm; 1 in. = 2.54 cm.

The modulus for the AC surface layer should be determined based on a design pavement temperature for input to Figure 3. The method of selecting the design pavement temperature for this evaluation is taken from Brabston et al.[17] Witczak[18] presents a relationship between pavement temperature and air temperature (Figure 23) that can be used to determine the design pavement temperature if the corresponding design air temperature is known. For this design procedure, the design air temperature for a particular locale is determined by averaging the average daily maximum

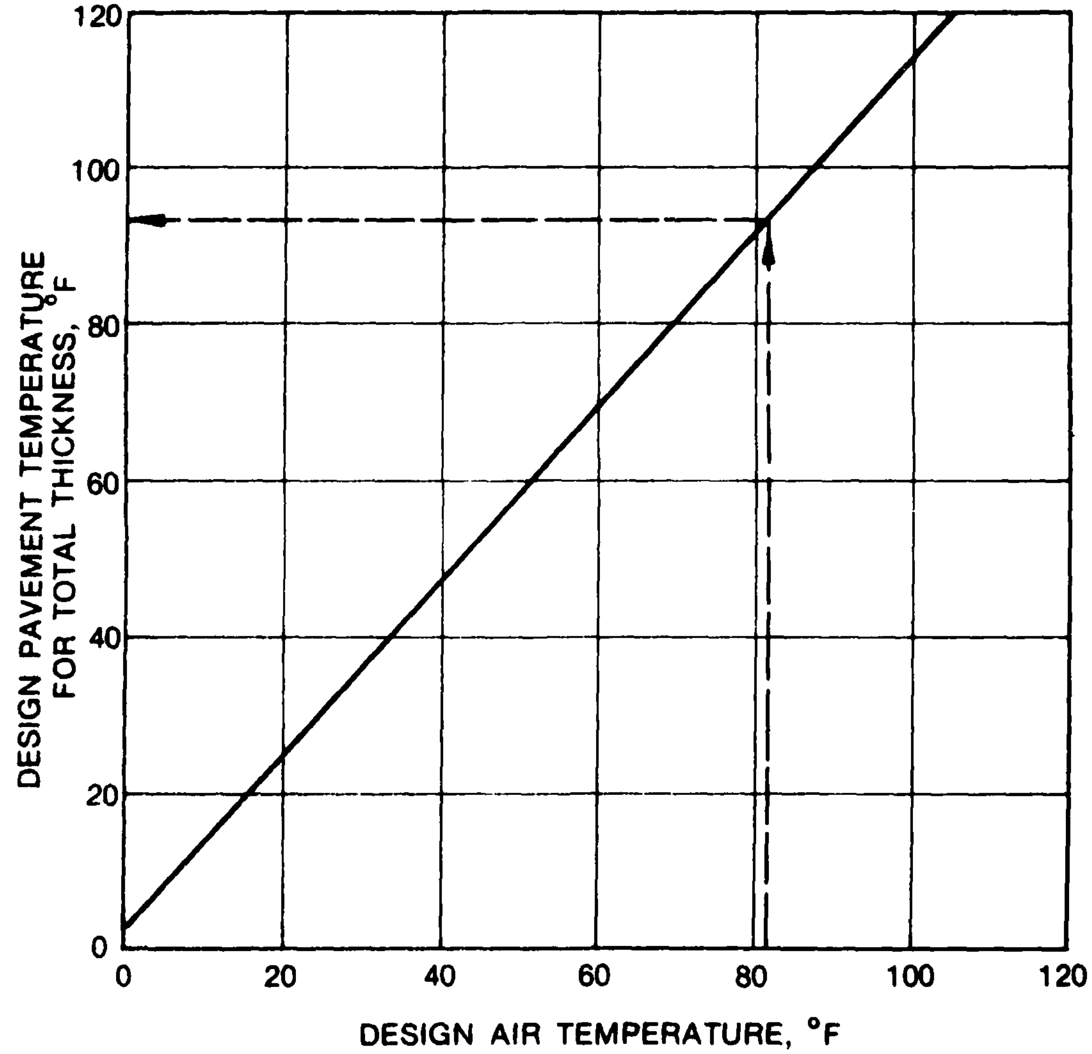


Figure 23. Relationship between design pavement temperature and design air temperature (1°F = -17°C)

temperature and the average daily mean temperature for the design month. Generally, the set of average temperatures will be necessary only for the hottest month indicated in the reporting period.

This method of calculating a design modulus for the AC layer is conservative. Other procedures have been reported by Barker and Brabston[14] and Koole.[6] Modulus values of those layers of base and subbase should be selected from the CHEVDEF output for the high-load (7000-lb) data. These values approximate the stress of the light aircraft and should be representative for the behavior when an elastic model is used.

The PAVEVAL program has the capability of calculating AC and PCC overlays. These procedures are available in the Weiss[3] report but were not evaluated for use in light aircraft pavement design as a part of this study. The computer program listed in Appendix B may be reproduced for use by any interested party.

CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in the development of an evaluation procedure for light aircraft pavements based on a layered elastic model. Nondestructive pavement test results are used to predict the layer strength parameters that can be input into a layered elastic model to predict the allowable load-carrying capacities of both rigid and flexible pavements containing either stabilized or nonstabilized layers.

The deflection basins measured from the NDT device at two force levels are used for input to a system that predicts the nonlinear stress-dependent behavior of the subgrade material. Results compare favorably with laboratory resilient modulus tests.

It is recommended that this procedure be adopted for use in evaluating light aircraft pavements. Further study should be conducted to make this approach applicable to air carrier airport pavements. The use of a finite element code for the modeling of a rigid plate and the nonlinear behavior of the granular materials should be included in future studies.

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APPENDIX A: LABORATORY PROCEDURE FOR DETERMINING THE RESILIENT MODULUS OF SUBGRADE SOILS*

The objective of this test procedure is to determine a modulus value for subgrade soils by means of resilient triaxial techniques. The test is similar to a standard triaxial compression test, the primary exception being that the deviator stress is applied repetitively and at several stress levels. This procedure allows testing of soil specimens in a repetitive stress state similar to that encountered by a soil in a pavement under a moving wheel load.

DEFINITIONS

The following symbols and terms are used in the description of this procedure:

a. σ_1 = total axial stress.

b. σ_3 = total radial stress; i.e., confining pressure in the triaxial test chamber.

c. $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress; i.e., the repeated axial stress in this procedure.

d. ϵ_1 = total axial strain due to σ_d .

e. $M_R = \sigma_d/\epsilon_{R_1}$ = resilient modulus.

f. $\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$ = sum of the principal stresses in the triaxial state of stress.

g. σ_1/σ_3 = principal stress ratio.

h. Load duration = time interval over which the specimen is subjected to a deviator stress.

i. Cycle duration = time interval between successive applications of a deviator stress.

SPECIMENS

Various diameter soil specimens may be used in this test, but the recommended specimen diameter is 2.5 to 3.0 in. or approximately four times maximum aggregate size. The specimen height should be at least twice the diameter. Undisturbed or laboratory molded specimens can be used. Procedures for obtaining undisturbed soil specimens are given in

---

* This procedure is taken from the report by Barker and Brabston.[14]

Engineer Manual 1110-2-1907, "Soil Sampling."[19] Methods for laboratory preparation of molded specimens and for back-pressure saturation of specimens, if required, are presented in EM 1110-2-1906, "Laboratory Soils Testing."[20]

EQUIPMENT

TRIAXIAL TEST CELL

A triaxial cell suitable for use in resilience testing of soils is shown in Figure A-1. This equipment is similar to most standard cells, with the exceptions of being somewhat larger to facilitate the internally mounted load and deformation measuring equipment and having additional outlets for the electrical leads from the measuring devices. For the type of equipment shown, air or nitrogen is used as the cell fluid.

The external loading source may be any device capable of providing a variable load of fixed cycle and load duration, ranging from simple cam-and-switch control of static weights or air pistons to a closed-loop electrohydraulic system. A load duration of 0.2 sec and a cycle duration of 3 sec have been found to be satisfactory for most applications. A square-wave load form is recommended.

DEFORMATION MEASURING EQUIPMENT

The deformation measuring equipment consists of linear variable differential transducers (LVDT's) attached to the soil specimen by a pair of clamps. Two LVDT's are used for the measurement of axial deformation. The clamps and LVDT's are shown in position on a soil specimen in Figure A-1. Details of the clamps are shown in Figure A-2. Load is measured by placing a load cell between the specimen cap and the loading piston as shown in Figure A-1.

Use of the type of measuring equipment described above offers several advantages:

- a. It is not necessary to reference deformations to the equipment, which deforms during loading.
- b. The effect of end-cap restraint on soil response is virtually eliminated.

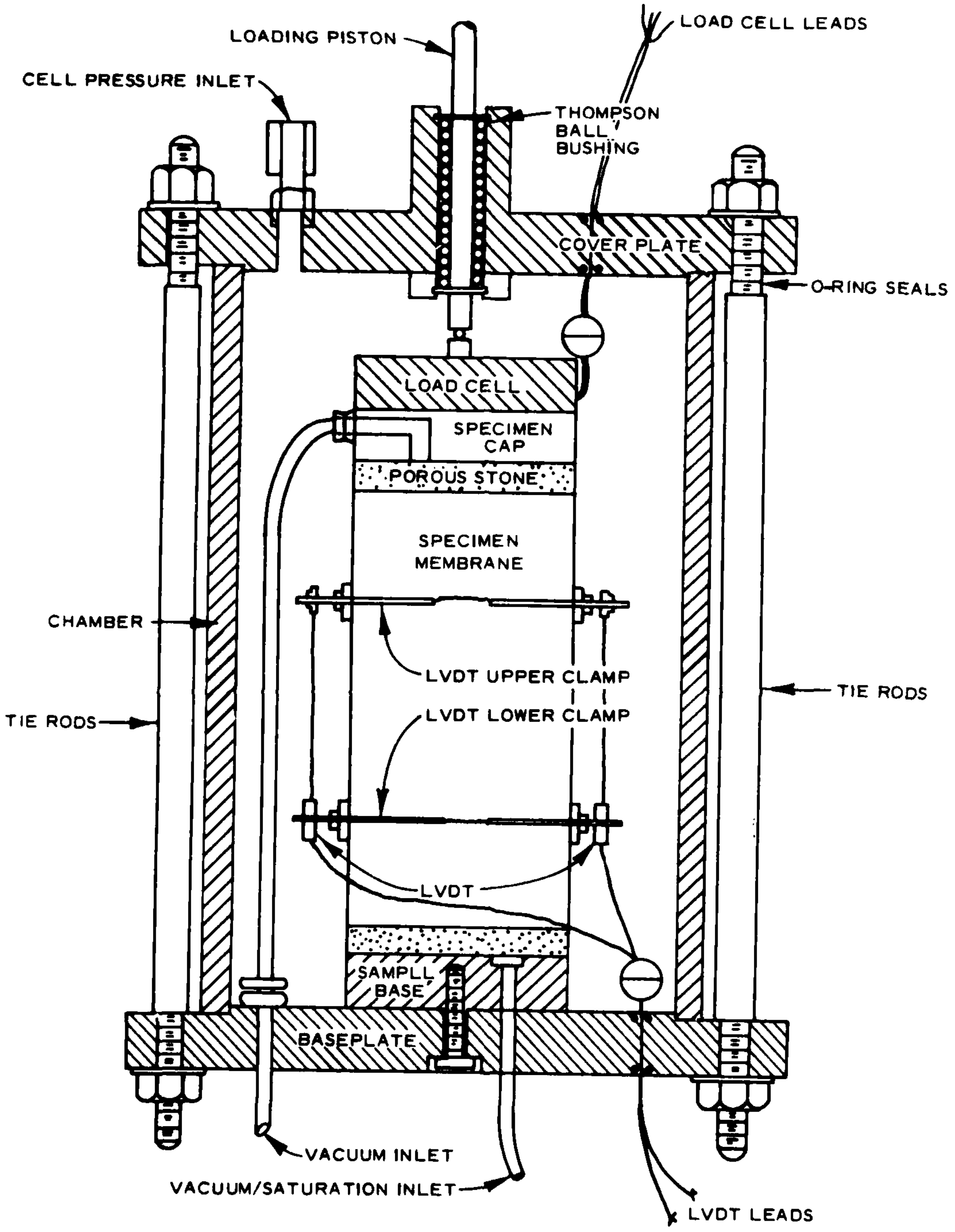
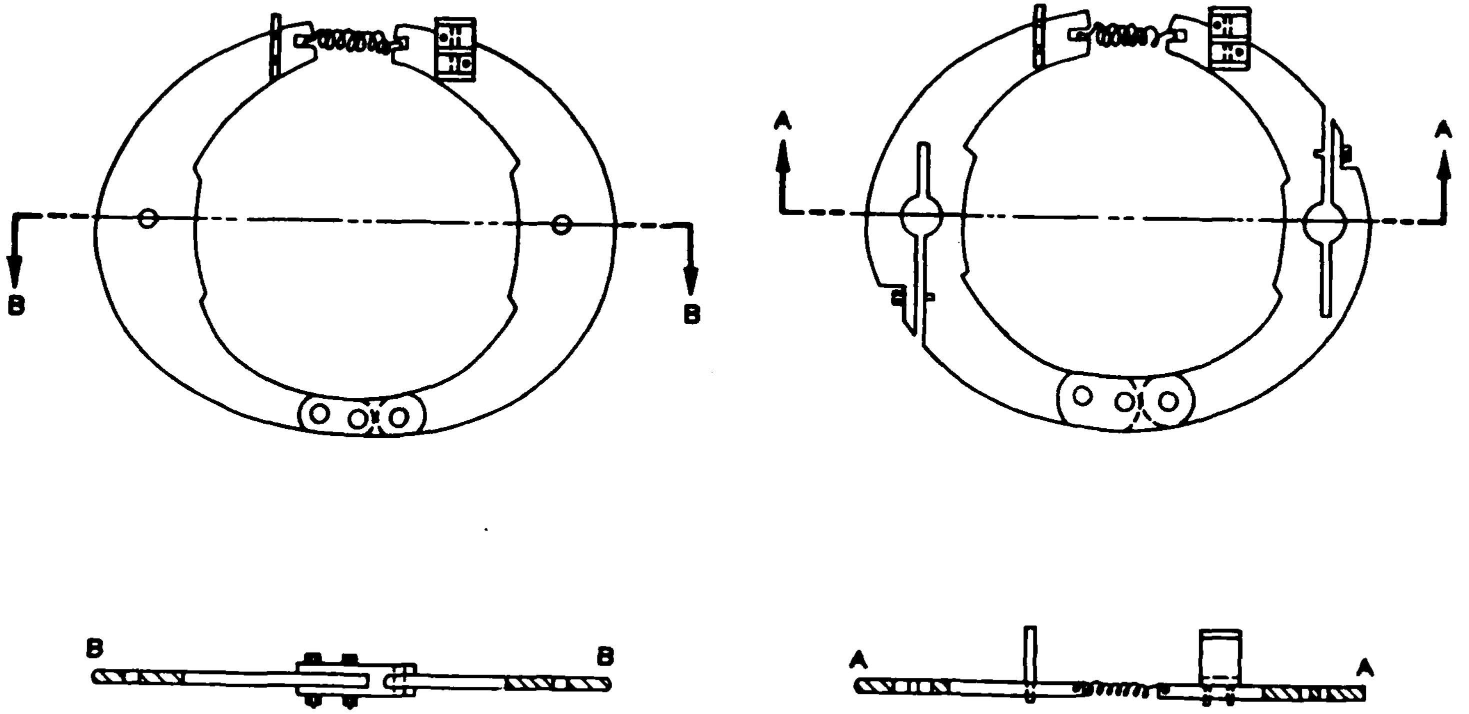


Figure A-1. Triaxial cell



a. UPPER CLAMP

b. LOWER CLAMP

Figure A-2. LVDT clamps

c. Any effects of piston friction are eliminated by measuring loads inside the triaxial cell.

In addition to the measuring devices, it is also necessary to maintain suitable recording equipment. It is desirable to have simultaneous recording of load and deformation. The number of recording channels can be reduced by wiring the leads from the LVDT's so that only the average signal from each pair is recorded. The introduction of switching and balancing units permits use of a single-chamber recorder. However, this will not permit simultaneous recording.

ADDITIONAL EQUIPMENT

In addition to the equipment described above, the following items are also used:

a. A 10- to 30-ton-capacity loading machine.

b. Calipers, a micrometer gage, and a steel rule (calibrated to 0.01 in.).

c. Rubber membranes, 0.01 to 0.025 in. thick.

d. Rubber o-rings.

e. A vacuum source with a bubble chamber and regulator.

f. A back-pressure chamber with pressure transducers.

g. A membrane stretcher.

h. Porous stones.

PREPARATION OF SPECIMENS AND PLACEMENT IN TRIAXIAL CELL

The following procedure should be followed in preparing and placing specimens:

a. In accordance with procedures specified in EM 1110-2-1906,[20] prepare the specimen and place it on the base-plate complete with porous stones, cap, and base and equipped with a rubber membrane secured with O-rings. Check for leakage. If back-pressure saturation is anticipated for cohesive soils, procedures indicated in Appendix X to EM 1110-2-1906 for the Q-type triaxial tests should be followed. For purely noncohesive soils, it will be necessary to maintain the vacuum during placement of the LVDT's. The specimen is now ready to receive the LVDT's.

b. Extend the lower LVDT clamp and slide it carefully down over the specimen to approximately the lower quarter point of the specimen.

c. Repeat this step for the upper clamp, placing it at the upper quarter point. Insure that both clamps lie in horizontal planes.

d. Connect the LVDT's to the recording unit, and balance the recording bridges. This step will require recorder adjustments and adjustment of the LVDT stems. When a recording bridge balance has been obtained, determine (to the nearest 0.01 in.) the vertical spacing between the LVDT clamps and record this value.

e. Place the triaxial chamber in position. Set the load cell in place on the specimen.

f. Place the cover plate on the chamber. Insert the loading piston, and obtain a firm connection with the load cell.

g. Tighten the tie rods firmly.

h. Slide the assembled apparatus into position under the axial loading device. Bring the loading device to a position in which it nearly contacts the loading piston.

i. If the specimen is to be back-pressure saturated, proceed in accordance with EM 1110-2-1906.

j. After saturation has been completed, rebalance the recorder bridge to the load cell and LVDT's.

RESILIENCE TESTING OF COHESIVE SOILS

The resilient properties of cohesive soils are only slightly affected by the magnitude of the confining pressure σ_3. For most applications, this effect can be disregarded. When back-pressure saturation is not used, the confining pressure used should approximate the expected in situ horizontal stresses, which will generally be on the order of 1 to 5 psi. A chamber pressure of 2 psi is a reasonable value for most testing. If back-pressure saturation is used, the chamber pressure will depend on the required saturation pressure.

Resilient properties are highly dependent on the magnitude of the deviator stress σ_d. It is therefore necessary to conduct the tests for a range in deviator stress values. The following procedure should be followed:

a. If back-pressure saturation is not used, connect the chamber pressure supply line and apply the confining pressure (equal to the chamber pressure). If back-pressure saturation is used, the chamber pressure will already have been established.

b. Rebalance the recording bridges for the LVDT's, and balance the load cell recording bridge.

c. Begin the test by applying 1000 repetitions of a deviator stress of not more than one-half the unconfined compressive strength.

d. Decrease the deviator load to the lowest value to be used. Apply 200 repetitions of load, recording the recovered vertical deformation at or near the last repetition.

e. Increase the deviator load, recording deformations as in Step d. Repeat over the range of deviator stresses to be used. It is recommended that 3, 5, 7, 12, 15, 17, 20, 22, and 25 psi be used.

f. At the completion of the loading, reduce the chamber pressure to zero. Remove the chamber LVDT's and load cell. Use the entire specimen for the purpose of determining the moisture content.

The results of the resilience tests can be presented graphically as shown in Figure A-3 for the resilient modulus and in the form of a summary table such as Table A-1.

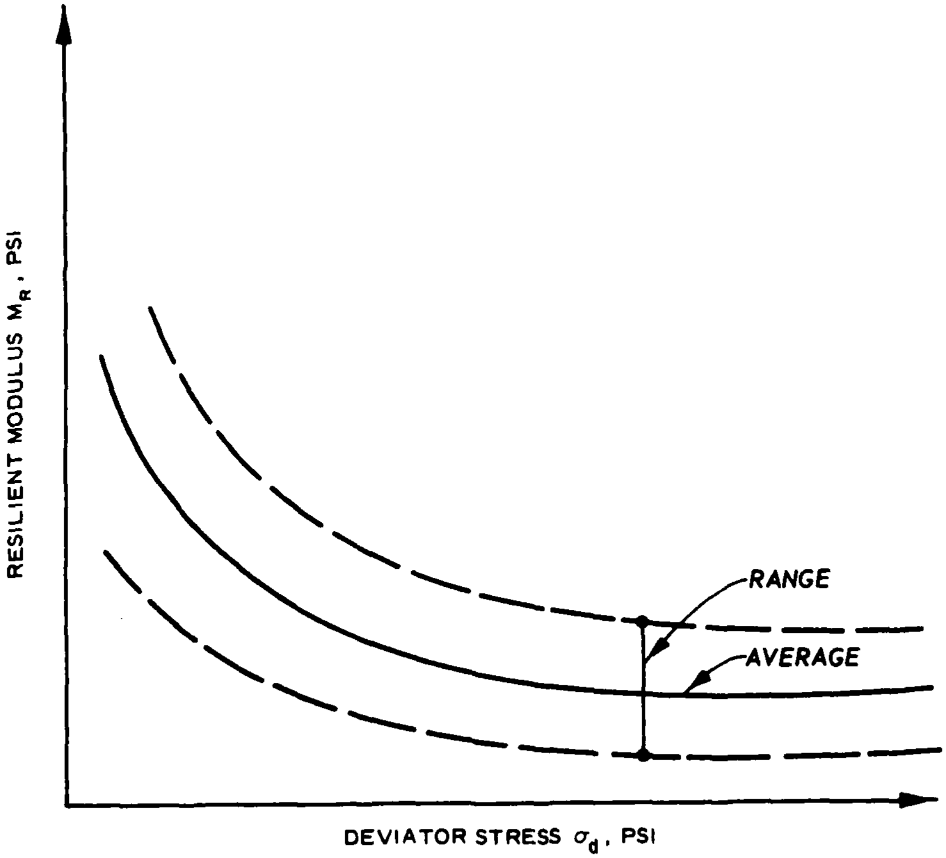


Figure A-3. Presentation of results of resilience tests on cohesive soils (1 psi = 703 kg/m^2)

Table A-1

Example Data Form for Recording Results of Resilience Tests of Cohesive Soils

Soil Sample ____________
____
____
Location ____________
Sample No. ____________
Specific Gravity ____________

Soil Specimen Measurements

Diameter
Top ____________
Middle ____________
Bottom ____________
Average ____________
Membrane Thickness ____________
Net Diameter ____________
Ht. Specimen + Cap + Base ____________
Ht. Cap + Base ____________
Initial Length L_0 ____________

Soil Specimen Weight

Initial Wt. of Container + Wet Soil - gms ____________
Final Wt. of Container + Wet Soil - gms ____________
Wt. Wet Soil Used ____________

Soil Specimen Volume

Initial Area A_0 **in (inch)^2** ____________
Volume A_0L_0 **in (inch)^3** ____________
Wet Density - pcf ____________
Water Content - % ____________
% Saturation ____________
Dry Density - pcf ____________

Date ____________
Compaction Method ____________
____
Vertical Spacing Between LVDT Clamps - inch ____________
Chamber Pressure - psi ____________

Constants

Vertical LVDT ____________
Load Cell ____________
Comments ____________
____
____

Load Cell Chart Reading	Deviator Load lbs	σ_d psi	Vertical LVDT Chart Reading	Vertical Defor-mation Inches	ϵ_{R1} in/in	$M_R = \sigma_d/\epsilon_{R1}$ psi

Note: 1 in. = 2.54 cm; 1 in.^{2} = 6.45 cm^2; 1 in.^{3} = 16.39 cm^3; 1 pcf = 16.02 kg/m^3; 1 psi = 703 kg/m^2

RESILIENCE TESTING OF COHESIONLESS SOILS

The resilient modulus of cohesionless soils M_R is dependent upon the magnitude of the confining pressure σ_3 and is nearly independent of the magnitude of the repeated axial stress. Therefore, it is necessary to test cohesionless materials over a range of confining and axial stresses. (The confining pressure is equal to the chamber pressure less the back pressure for saturated specimens.) The following procedures should be used for this type of test:

a. Use confining pressures of 5, 10, 15, and 20 psi. At each confining pressure, test at five values of the principal stress difference corresponding to multiples (1, 2, 3, 5) of cell pressure.

b. Before beginning to record deformations, apply a series of conditioning stresses to the material to eliminate initial loading effects. The greatest amount of volume change occurs during the application of the conditioning stresses. Simulation of field conditions suggests that drainage of saturated specimens should be permitted during the application of these loads but that the test loading (beginning in Step f below) should be conducted in an undrained state.

c. Set the axial load generator to apply a deviator stress of 10 psi (i.e., a stress ratio equal to 3). Activate the load generator and apply 200 repetitions of this load. Stop the loading.

d. Set the axial load generator to apply a deviator stress of 20 psi (i.e., a stress ratio equal to 3). Activate the load generator and apply 200 repetitions of this load. Stop the loading.

e. Repeat as in Step d above maintaining a stress ratio equal to 6 and using the following order and magnitude of confining pressures: 10, 20, 10, 5, 3, and 1 psi.

f. Begin the record test using a confining pressure of 1 psi and an equal value of deviator stress. Record the resilient deformation after 200 repetitions. Increase the deviator stress to twice the confining pressure and record the resilient deformation after 200 repetitions. Repeat until a deviator stress of 5 times the confining pressure is reached (stress ratio of 6).

g. Repeat as in Step f above for each value of confining pressure.

h. When the test is completed, decrease the back pressure to zero, reduce the chamber pressure to zero, and dismantle the cell. Remove the LVDT clamps, etc. Remove the soil specimen, and use the entire amount of soil to determine the moisture content.

Test results should be presented in the form of a plot of log M_R versus log of the sum of the principal stresses as shown in Figure A-4. Calculations can be performed using the tabular arrangement shown in Table A-2.

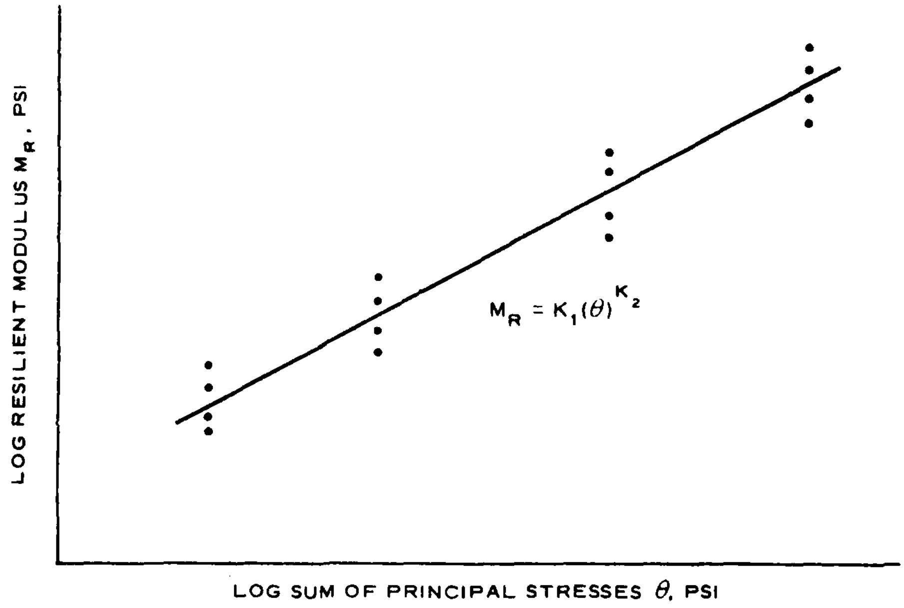


Figure A-4. Presentation of results of resilience tests on cohesionless soils (1 psi = 703 kg/m^2)

Table A-2

Example Date Form for Recording Results of Resilience Tests of Cohesionless Soils

Soil Sample____________________

Location____________________
Sample No.____________________
Specific Gravity____________________

Soil Specimen Measurements

Diameter
- **Top**____________________
- **Middle**____________________
- **Bottom**____________________
- **Average**____________________

Membrane Thickness____________________
Net Diameter____________________
Ht. Specimen + Cap + Base____________________
Ht. Cap + Base____________________
Initial Length L_0____________________

Soil Specimen Weight

Initial Wt. of Container + Wet Soil - gms ____________________
Final Wt. of Container + Wet Soil - gms ____________________
Wt. Wet Soil Used ____________________

Soil Specimen Volume

Initial Area A_0 **in (inch)^2** ____________________
Volume A_0L_0 **in (inch)^2** ____________________
Wet Density pcf ____________________
Water Content - % ____________________
% Saturation ____________________
Dry Density - pcf ____________________
Void Ratio ____________________

Date ____________________

Compaction Method ____________________

Vertical Spacing Between LVDT Clamps - inch ____________________

Constants

Vertical LVDT ____________________

Load Cell ____________________

Comments ____________________

Confining Pressure psi (σ_3)	Load Cell Chart Reading	Deviator Load lbs.	$\sigma_d = \sigma_1 - \sigma_3$ psi	$\frac{\sigma_1}{\sigma_3}$	θ psi	Vertical LVDT Chart Reading	Vertical Defor-mation inch	ϵ_{R1} in/in	$M_R = \sigma_d/\epsilon_{R1}$ psi

Note: 1 in. = 2.54 cm; 1 in.^{2} = 6.45 cm^2; 1 in.^{3} = 16.39 cm^3; 1 pcf = 16.02 kg/m^3; 1 psi = 703 kg/m^2

APPENDIX B: CHEVDEF PROGRAM

INTRODUCTION

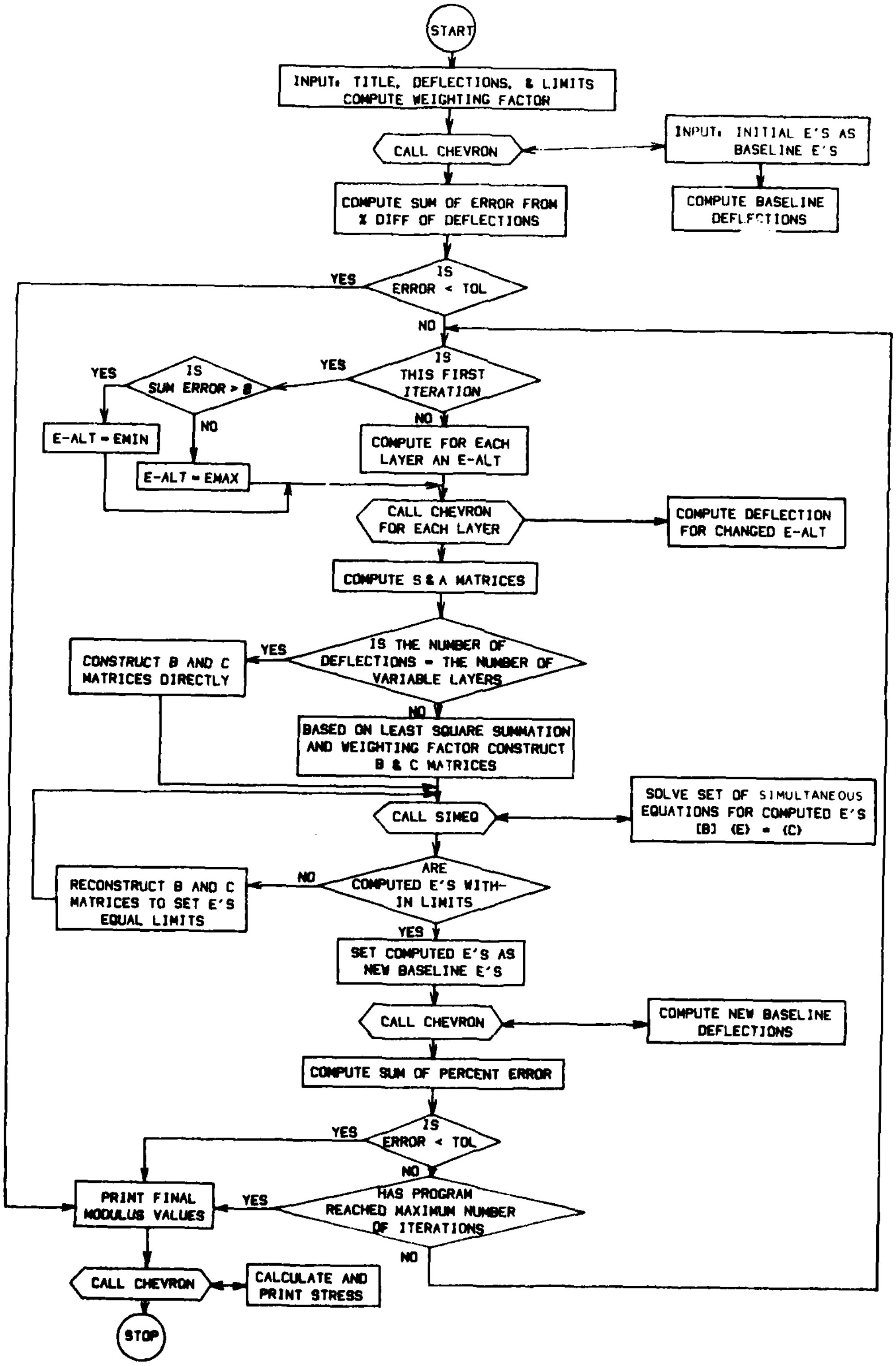
The CHEVDEF program takes measured deflections from a deflection basin with initial estimates and ranges of layer modulus and computes the modulus values that best describe the input deflection basin. A linearly layered elastic computer program originally developed by Chevron Oil Company is used as a subroutine to calculate the stress, strains, and deflections.

The information provided herein is as follows:

- a. Flowchart.
- b. Input guide.
- c. Example input.
- d. Example output.
- e. Program listing.

FLOWCHART

A flowchart describing the logic of the program is presented on the following page.


START
INPUT: TITLE, DEFLECTIONS, & LIMITS
COMPUTE WEIGHTING FACTOR
CALL CHEVRON
INPUT: INITIAL E'S AS BASELINE E'S
COMPUTE BASELINE DEFLECTIONS
COMPUTE SUM OF ERROR FROM % DIFF OF DEFLECTIONS
IS ERROR < TOL
YES
NO
IS THIS FIRST ITERATION
YES
IS SUM ERROR > 0
YES
NO
E-ALT = EMIN
E-ALT = EMAX
NO
COMPUTE FOR EACH LAYER AN E-ALT
CALL CHEVRON FOR EACH LAYER
COMPUTE DEFLECTION FOR CHANGED E-ALT
COMPUTE S & A MATRICES
IS THE NUMBER OF DEFLECTIONS = THE NUMBER OF VARIABLE LAYERS
YES
CONSTRUCT B AND C MATRICES DIRECTLY
NO
BASED ON LEAST SQUARE SUMMATION AND WEIGHTING FACTOR CONSTRUCT B & C MATRICES
CALL SIMEQ
SOLVE SET OF SIMULTANEOUS EQUATIONS FOR COMPUTED E'S [B] {E} = {C}
ARE COMPUTED E'S WITHIN LIMITS
NO
RECONSTRUCT B AND C MATRICES TO SET E'S EQUAL LIMITS
YES
SET COMPUTED E'S AS NEW BASELINE E'S
CALL CHEVRON
COMPUTE NEW BASELINE DEFLECTIONS
COMPUTE SUM OF PERCENT ERROR
IS ERROR < TOL
YES
NO
HAS PROGRAM REACHED MAXIMUM NUMBER OF ITERATIONS
YES
NO
PRINT FINAL MODULUS VALUES
CALL CHEVRON
CALCULATE AND PRINT STRESS
STOP

INPUT GUIDE

PROGRAM CHEVDEF
(Matching of Pavement Deflections Using CHEVRON Layered Elastic Computer Program)

Line 1

LINENU	NPROB

NPROB = Number of data sets

Line 2

Title 72 characters

Note: Line 2 through Line 13 are repeated for each data set.

Line 3

LINENU	ND	RRD(1)	--	--	RRD(ND)

ND = Number of deflection reasings (maximum of 4)

RRD(i) i = 1, ND = Measured deflections in mils

Line 4

LINENU	NL	TOL	MAXIT

NL = Number of variable layers for which the modulus is to be determined (not to exceed the number of deflections)

TOL = Tolerance in percent for stopping programs (usually = 10)

MAXIT = Maximum number of iterations (usually = 3)

Line 5-1 through 5-NL (one line for each unknown modulus)

LINENU	ILV(i)	EMIN(i)	EMAX(i)

ILV(i) = System layer number for unknown modulus value i

EMIN(i) = Minimum allowable modulus for unknown modulus i

EMAX(i) = Maximum allowable modulus for unknown modulus

Line 6

Title at start of CHEVRON data 72 characters

Line 7

LINENU	WGT	PSI	NOUTP	NPUN

WGT = Total load applied to pavement

PSI = Contact pressure of load

NOUTP = Control output : set = 0

NPUN = Control output : set = 1

Line 8 (continue to additional lines as necessary for all E's and V's)

LINENU	NS	E(i)	V(i)	--	--	E(NS)	V(NS)

NS = Total number of layers in system

E(i) = Starting modulus for layers i = 1, NS

V(i) = Poisson's ratio for layers i = 1, NS

Line 9

LINENU	HH(1)	HH(2)	--	--	HH(NS-1)

HH(i) = Thickness of layer i = 1, NS-1

Line 10

LINENU	iR	RR(1)	RR(2)	--	RR(iR)

iR = Number of radial offsets (set = ND)

RR(i) i = 1, iR = Distance to deflection readings

Line 11

LINENU	iZ	ZZ(1)

iZ = Number of depth set = 1

ZZ(1) = Depth of deflection set = 0

Note: After determination of final modulus subgrade, CHEVRON is called for computation of stress, strains, and deflection at selected points. These soils should be the center of granular layers and the top of the subgrade material.

Line 12

LINENU	iR	RR(1)	RR(2)	--	RR(iR)

iR = Number of offsets (f iR = 0 returns for new data set)

RR(i) i = 1, iR = Distance to selected points

Line 13

LINENU	iZ	ZZ(1)	ZZ(2)	--	RR(iZ)

iZ = Number of depth

ZZ(i) i = 1, iZ = Depth to selected points

Note: Run is now terminated or returned for new data.
For devices with two loaded areas, use total force
on one area and compute radial distances for Line 10.

EXAMPLE INPUT

An example input for the PTRF 1A item is listed below. Control cards preceeding input are for the Honeywell G635 Computer in the remote batch mode (CARDIN).

```
010##N(!)
020$!IDENT!R0SF300.CURTIS
030$!OPTION!FORTRAN
040$!USE!.GTLIT
050$!FORTY!XREF
060$!SELECTA!R0SF300/CHEVDEF
070$!EXECUTE
080$!LIMITS!40,30K,,6K
090 010 1
100 020PTRF 1A RR2008 DEFL. (7000 LB)
110 030 4,5.908,4.433,3.067,1.933
120 040 3,10,3
130 050 1,20000,700000
140 060 2,20000,100000
150 070 3,10000,30000
160 080 CHEVRON
170 090 7000,27.508,0,1
180 100 4,500000,0.35,50000,0.35,20000,0.4,1000000,0.5
190 110 7.5,20.5,212
200 120 4,4.5,12,24,36
210 130 1,0
220 140 1,0
230 150 2,7.5,28
240$ENDJOB
```

EXAMPLE OUTPUT

An example output for the PTRF 1A item is provided on the following pages. The number of problems to be solved is 1 .

```
020 PTRF 1A RR2008 DEFL. (7000 LB.)

    NUMBER OF VARIABLE LAYERS AND TARGET DEFLECTIONS =   3

                     DEFLECTION READINGS IN MILS
POSITION NO:                        1            2            3            4
DEFLECTIONS:                      5.908        4.433        3.067        1.933
WEIGHTING FACTOR:                 0.169        0.226        0.326        0.517



    VARIABLE     SYSTEM        VALUE OF            VALUE OF
    LAYER NO    LAYER NO    MAXMUM MODULUS     MINIMUM MODUL   US
       1           1           700000.0            20000.0
       2           2           100000.0            20000.0
       3           3            30000.0            10000.0


*****080 START DATA FOR CHEVRON

                        THE PROBLEM PARAMETERS ARE

    TOTAL LOAD..            7000.00  LBS

    TIRE PRESSURE..           27.51  PSI

    LOAD RADIUS..              9.00  IN.

    LAYER NO.         MODULUS        POISSONS RATIO        THICKNESS

        1             500000.            0.350                7.50

        2              50000.            0.350               20.50

        3              20000.            0.400              212.00

        4            1000000.            0.500            SEMI-INFINITE

  POSITION   DEFLECTION   MEASURED    DIFFERENCE   % DIFF.
      1        5.5500      5.9080       0.3580       6.1
      2        4.2409      4.4330       0.1921       4.3
      3        2.8706      3.0670       0.1964       6.4
      4        2.0131      1.9330      -0.0801      -4.1
                       ABSOLUTE SUM:    0.8265     20.9390
                     ARITHMETIC SUM:               12.6527
```

```
     DATA FOR DEVELOPING EQUATIONS FOR ITERATIONS      NO.  1


     LAYER    INITIAL    CHANGED        OFFSET             DEFLECTIONS
     NO.      MODULUS    MODULUS        DIST.     INITIAL        CHANGED   READIN
GS
*****************************************************************************
       1      500000.     20000.          4.50     5.550          14.501     5.908
                                         12.00     4.241           5.428     4.433
                                         24.00     2.871           3.023     3.067
                                         36.00     2.013           2.102     1.933
*****************************************************************************
       2       50000.     20000.          4.50     5.550           7.686     5.908
                                         12.00     4.241           5.981     4.433
                                         24.00     2.871           3.808     3.067
                                         36.00     2.013           2.391     1.933
*****************************************************************************
       3       20000.     10000.          4.50     5.550           7.507     5.908
                                         12.00     4.241           6.037     4.433
                                         24.00     2.871           4.609     3.067
                                         36.00     2.013           3.542     1.933
*****************************************************************************


PREDICTED E DISREGARDING BOUNDARY CONDITIONS
    500060.        40304.        21130.

    POSITION  DEFLECTION    MEASURED     DIFFERENCE    % DIFF.
        1       5.8718       5.9080        0.0362        0.6
        2       4.4794       4.4330       -0.0464       -1.0
        3       2.9416       3.0670        0.1254        4.1
        4       1.9892       1.9330       -0.0562       -2.9
                       ABSOLUTE SUM:       0.2642      8.6555
                     ARITHMETIC SUM:                    0.7480
                            AVERAGE:       0.0661      2.1639

  THE FINAL MODULUS VALUES ARE

  500060.        40304.          21130.        1000000.
    DEFLECTIONS ARE IN TOLERANCE
 R   Z              VERTICAL   TANGENTIAL     RADIAL        SHEAR        BULK


 0.    -7.5 STRE   -9.397E 00   4.723E 01   4.723E 01   0.            8.507E 01
            STRA   -8.491E-05   6.797E-05   6.797E-05   0.            5.103E-05
            DSPL    5.909E-03

 0.     7.5 STRE   -9.397E 00  -8.452E-01  -8.452E-01   0.           -1.109E 01
            STRA   -2.185E-04   6.797E-05   6.797E-05   0.           -8.253E-05
            DSPL    5.909E-03

 0.   -28.0 STRE   -2.019E 00   1.313E 00   1.313E 00   0.            6.064E-01
            STRA   -7.291E-05   3.871E-05   3.871E-05   0.            4.514E-06
            DSPL    3.439E-03

 0.    28.0 STRE   -2.019E 00   1.701E-02   1.701E-02   0.           -1.985E 00
            STRA   -9.621E-05   3.871E-05   3.871E-05   0.           -1.879E-05
            DSPL    3.439E-03
***** END OF PROGRAM *****
```

PROGRAM LISTING

```
HIS SERIES 600 ON  11 10 80 AT 12.555  CHANNEL 6007

SYSTEM ?FORT
OLD OR NEW-OLD CHEVDEF
OLD OR NEW-OLD
OLD FILE? CHEVDEF
READY
*LIST

00010C************************************************************************
00020C************************************************************************
00030C
00040C
00050C          THIS PROGRAM CONTAINS AN ITERATIVE PROCEDURE TO CALCULATE
00060C    MODULUS VALUES FOR UP TO 4 PAVEMENT LAYERS FROM THE DEFLECTION
00070C    BASIN MEASUREMENTS.  THE PROGRAM USES THE CHEVRON N - LAYER
00080C    ELASTIC SYSTEMS PROGRAM AS A SUBROUTINE TO CALCULATE DEFLECTIONS
00090C    FROM INITIAL AND ITERATIVE MODULUS VALUES.
00100C
00110C
00120C
00130C                         PROGRAM NAME:  CHEVDEF
00140C
00150C                         CODED BY:  DR. WALTER R BARKER
00160C
00170C                         POINT OF CONTACT:
00180C                             ALBERT J. BUSH, III
00190C                             GEOTECHNICAL LABORATORY
00200C                             WATERWAYS EXPERIMENT STATION
00210C                             VICKSBURG, MISSISSIPPI  39180
00220C
00230C                         COMPUTER:  WATERWAYS EXPERIMENT STATION, GE635
00240C                         LANGUAGE:  FORTRAN IV
00250C                         DATE COMPLETED:  JULY 1980
00260C                         SPECIAL REQUIREMENT:  CARDIN: REMOTE BATCH PROCESSING
00270C                         STORAGE:  DISC
00280C
00290C
00300C************************************************************************
00310C************************************************************************
00320C*****
00330C
00340C
00350C******
00360C
00370       CALL FXOPT(67,1,1,0)
00380      LOGICAL RECALC,REITER,CONTIN
00390      CHARACTER*80 TEXT1
00400      CHARACTER*4 CONPAR
00410      CHARACTER IFUN*1(4,4)
00420      INTEGER COUNTR
00430      DIMENSION EL(4,3),EMAX(4),EMIN(4),S(4,4),A(4,4),C(4),B(4,4)
00440     &,AK(9),          ILV(4),NDF(4),IDF(4,4)
00450     &    ,W(4),ATEMP(10)
00460      REAL MOISC,NU,STEMP(4),RTEMP(4,4)
00470     &,ETOL(4),DF(4,3),         RRD(4),DTOL(4),
00480     &TEMPDEF(4),PCT(4),ACCUR(2)
00490      COMMON OPT COUNTR,DEF(4),NLAYS
00500      COMMON    RMCOY AX1(10),   ZZ(10),   E(5),     V(5),     HH(4),
00510     &          H9(4),      AZ(396),  A9(396,5), B9(396,5), C9(396,5),
00520     &                D(396,5), AJ(396),  RJ1(396), RJ0(396), TITLE(20),
00530     &                TEXT(11), RZ(100),  X(5,4,4),  IC(4),    FM(2,2),
00540     &                RM(4,4,4),   DUMMY(4)
```

```
      DATA CONPAR/ N
      READ(5,210) LINENU, NPROB
      WRITE(6,105) NPROB
      DO 9999 NPR=1,NPROB
      WRITE(6,1212) NPR
 9999 CONTINUE
      READ(5,1000)TEXT1
      WRITE(6,200)TEXT1
      READ(5,210) LINENU,ND,(RPD(I),I=1,ND)
      SUM = 0.
      COUNTR=1
    1 CONTINUE
      ITER=0
      READ(5,210) LINENU,NL,TOL,MAXIT
      DO 5 I =1,ND
      W(I) = 1./RPD(I)
    5 CONTINUE
      DO 8 I=1,NL
      READ(5,210) LINENU,NW,EMIN(I),EMAX(I)
    8 ILV(I)=NW
      WRITE(6,600)NL
      WRITE(6,619) (I,I=1,ND)
      WRITE(6,620) (RPD(I),I=1,ND)
      WRITE(6,621) (W(I),I=1,ND)
      WRITE(6,790)
      WRITE(6,650)
      DO 59 MS=1,NL
      WRITE(6,660)MS,ILV(MS),EMAX(MS),EMIN(MS)
   59 CONTINUE
      CALL CHEVRON
      WRITE(6,830)
      CONTIN = .TRUE.
      SUM = 0.
      SUMP = 0.0
      ASUM=0.0
      DO 9 I = 1,ND
      ERR = RPD(I)-DEF(I)
      PERC=(ERR/RPD(I))*100
      SUM = SUM + ABS(ERR)
      SUMP = SUMP + ABS(PERC)
      ASUM = ASUM+PERC
      WRITE(6,820)I,DEF(I),RPD(I),ERR,PERC
      DF(I,3) = DEF(I)
 9    CONTINUE
      IF (SUMP.GT.TOL) CONTIN = .FALSE.
      WRITE (6,840) SUM,SUMP,ASUM
      IF (CONTIN) GOTO 89
      COUNTR=3
  6   ITER=ITER+1
      DO 15 I = 1,NL
      K = ILV(I)
      EL(I,3) = ALOG10(E(K))
 15   CONTINUE
      WRITE(6,760) ITER
      DO 60 JX=1,NL
      K=ILV(JX)
      IF(ITER.EQ.1)GO TO 21
      IF(C(JX).EQ.CTEMP(JX))
     &CTEMP(JX)=(ALOG10(EMAX(JX))+ALOG10(EMIN(JX)))/2
      EL(JX,1)=(3*C(JX)+CTEMP(JX))/4
```

```
01150       IF(ABS(E(K)-EMAX(JX)).LT.100.OR.ABS(E(K)-EMIN(JX)).LT.100)GO TO 24
01160       IF(C(JX).LT.CTEMP(JX))GO TO 23
01170       IF(ASUM.LT.0)EL(JX,1)=(3*C(JX)+ALOG10(EMAX(JX)))/4
01180       GO TO 24
01190    23 IF(ASUM.GT.0)EL(JX,1)=(3*C(JX)+ALOG10(EMIN(JX)))/4
01200    24 E(K)=10**EL(JX,1)
01210       GO TO 40
01220    21 IF(ASUM.LT.0)GO TO 30
01230       E(K)=EMIN(JX)
01240       GO TO 40
01250    30 E(K)=EMAX(JX)
01260    40 EL(JX,2)=ALOG10(E(K))
01270       CALL CHEVRON
01280       DO 50 KK =1,ND
01290       DF(KK,2) = DEF(KK)
01300    45 CONTINUE
01310       S(KK,JX)=(DF(KK,2)-DF(KK,3))/(EL(JX,2)-EL(JX,3))
01320       A(KK,JX)=DF(KK,2)-EL(JX,2)*S(KK,JX)
01330    50 CONTINUE
01340       ET3 = 10**EL(JX,3)
01350       WRITE(6,770)ILV(JX),ET3,E(ILV(JX)),AX1(1),DF(1,3),DEF(1),RPD(1)
01360        IF(ND.EQ.1) GO TO 39
01370        DO 34 JS =2,ND
01380        WRITE(6,780)AX1(JS),DF(JS,3),DEF(JS),RRD(JS)
01390 34     CONTINUE
01400 39     CONTINUE
01410       WRITE(6,810)
01420       E(K) = 10**EL(JX,3)
01430    60 CONTINUE
01440       DO 65 KK = 1,ND
01450    65 CONTINUE
01460       DO 69 KK = 1,ND
01470 69    CONTINUE
01480       IF(NL.NE.ND) GO TO 101
01490       DO 120 I = 1,NL
01500       C(I) = RPD(I)-A(I,NL)-S(I,NL)*EL(NL,3)
01510       DO 110 J = 1,NL
01520        C(I)=C(I)+S(I,J)*EL(J,3)
01530       B(I,J) = S(I,J)
01540       BTEMP(I,J) = B(I,J)
01550 110    CONTINUE
01560        CTEMP(I) = C(I)
01570 120    CONTINUE
01580        GO TO 79
01590 101     CONTINUE
01600        DO 80 I = 1,NL
01610       C(I) = 0.0
01620       DO 70 J = 1,ND
01630       C(I) = C(I)+S(J,I)*(RPD(J)-A(J,NL)-S(J,NL)*EL(NL,3))*W(J)
01640       DO 67 JS = 1,NL
01650       C(I)=C(I) +S(J,JS)*S(J,I)*EL(JS,3)*W(J)
01660 67    CONTINUE
01670 70    CONTINUE
01680       DO 68 JS = 1,NL
01690       B(I,JS) = 0.
01700       DO 71 J = 1,ND
01710       B(I,JS) = B(I,JS) + S(J,I)*S(J,JS)*W(J)
01720 71     CONTINUE
01730       BTEMP(I,JS) = B(I,JS)
01740 68    CONTINUE
```

```
      CTEMP(I) = C(I)
   80 CONTINUE
   79 CONTINUE
      DO 78 NN=1,NL
   78 CONTINUE
      CALL SIMEQ(B,C,NL,KER,4)
      WRITE(6,301)
  301 FORMAT(1H )
      WRITE(6,301)
      WRITE(6,302)
  302 FORMAT(1H , PREDICTED E DISREGARDING BOUNDARY CONDITIONS )
       DO 73 JX =1,NL
       ATEMP(JX)=10**C(JX)
   73 CONTINUE
      WRITE(6,251)(ATEMP(JX),JX=1,NL)
      IF(KER.NE.0)GO TO 90
      RECALC=.FALSE.
      DO 84 I=1,NL
      IF(RECALC)GO TO 84
      AMAX = ALOG10(EMAX(I))
      AMIN = ALOG10(EMIN(I))
      IF(C(I).GE.(AMIN-.0001).AND.C(I).LE.(AMAX+.0001))GO TO 84
      RECALC=.TRUE.
      DO 82 K=1,NL
      IF(K.EQ.I)GO TO 86
      C(K)=CTEMP(K)
   86 DO 81 L=1,NL
      B(L,K)=BTEMP(L,K)
   81 CONTINUE
   82 CONTINUE
      IF(C(I).LT.AMIN)C(I)=AMIN
      IF(C(I).GT.AMAX)C(I)=AMAX
      CTEMP(I)=C(I)
      DO 83 K=1,NL
      B(I,K)=0.0
      BTEMP(I,K)=B(I,K)
   83 CONTINUE
      B(I,I)=1.0
      BTEMP(I,I)=B(I,I)
   84 CONTINUE
      IF(RECALC)GO TO 79
      DO 85 I=1,NL
      J=ILV(I)
      TEMP=10**C(I)
      TEMP1 = 10**EL(I,3)
      ETOL(I)=ABS(((TEMP-TEMP1)/TEMP1)*100)
      E(J)=TEMP
      CTEMP(I)=EL(I,3)
   85 CONTINUE
      CALL CHEVRON
      SUM = 0.
      SUMP = 0.0
      ASUM = 0.0
      CONTIN=.TRUE.
      WRITE(6,830)
      DO 88 I = 1,ND
      ERR = PRD(I)-DEF(I)
      PERC=(ERR/PRD(I))*100
      SUM = SUM + ABS(ERR)
      SUMP = SUMP + ABS(PERC)
```

```
      WRITE(6,820)I,DEF(I),PRD(I),ERR,PERC
      DF(I,3)=DEF(I)
       ASUM = ASUM + PERC
88     CONTINUE
      IF (SUMP.GT.TOL) CONTIN=.FALSE.
      PERSUM=SUM/ND
      PERSUMP=SUMP/ND
      WRITE(6,840) SUM,SUMP,ASUM
      WRITE(6,715)PERSUM,PERSUMP
      REITER = .TRUE.
      DO 87 I=1,NLAYS
      IF(ETOL(I).GT.TOL)REITER=.FALSE.
   87 CONTINUE
      IF (CONTIN) GOTO 89
      IF(REITER)GO TO 89
      IF(ITER.LT.MAXIT)GO TO 6
      WRITE(6,9000)(E(I),I=1,NLAYS)
      WRITE(6,310)
      WRITE(6,303)
  303 FORMAT(1H ,'REACHED MAX NO OF ITERATIONS')
      GOTO 10
  89  WRITE(6,9000)(E(I),I=1,NLAYS)
      IF(CONTIN) WRITE(6,304)
  304 FORMAT(1H ,'     DEFLECTIONS ARE IN TOLERANCE')
      IF(REITER) WRITE(6,305)
  305 FORMAT(1H ,'     CHANGE IN MODULUS VALUES ARE IN TOLERANCE')
   10 COUNTR=99
      CALL CHEVRON
      GO TO 9999
   90 WRITE(6,270)
 9999 CONTINUE
      WRITE(6,850)
      STOP
  105 FORMAT(1H1,10X,'THE NUMBER OF PROBLEMS TO BE SOLVED IS',
     &        2X,I3,///)
 820  FORMAT(5X,I5,3F12.4,F10.1)
  830 FORMAT(//,5X,'POSITION',2X,'DEFLECTION',3X,'MEASURED',3X,
     &'DIFFERENCE',3X,'% DIFF.')
 9000 FORMAT(/,3X,'THE FINAL MODULUS VALUES ARE',//,
     &4(F10.0,4X))
  200 FORMAT(1H ,A80)
  210 FORMAT(V)
  240 FORMAT(//,T30,'IN THE A MATRIX',//,T13,'1',T30,'2',T48,'3',
     &T68,'4',/)
  251 FORMAT(2X,4(F10.0,3X))
  250 FORMAT(2X,4(E16.6,3X))
  260 FORMAT(//,T30,'IN THE S MATRIX',//,T13,'1',T30,'2',T48,'3',
     & T68,'4'/)
  270 FORMAT('           THIS MATRIX HAS NO SOLUTION')
  290 FORMAT(//,T30,'IN THE B MATRIX',/,T13,'1',T30,'2',T48,'3',
     &T68,'4',/)
  300 FORMAT(//,T30,'IN THE C MATRIX',/,T13,'1',T30,'2',T48,'3',T68,'4'
     &,/)
  310 FORMAT(T25,'THE MODULUS VALUES ARE NOT WITHIN TOLERANCE')
 1000 FORMAT(A80)
  600 FORMAT(5X,'NUMBER OF VARIABLE LAYERS AND TARGET DEFLECTIONS =    ',
     &I2,/)
 619  FORMAT(1X,//,15X,'DEFLECTION READINGS IN MILS',/,
     & 'POSITION NO:',6X,4(9X,I1,2X))
 620  FORMAT('DEFLECTIONS:',6X,4(F12.3))
```

```
 621  FORMAT('WEIGHTING FACTOR: ',4(F12.3))
  650 FORMAT(/,5X,'VARIABLE     SYSTEM',9X,'VALUE OF',12X,'VALUE OF',/,
     &5X,'LAYER NO',3X,'LAYER NO',5X,'MAXMUM MODULUS',5X,'MINIMUM MODUL
     &US',/)
  660 FORMAT(9X,I2,9X,I2,10X,F10.1,10X,F10.1)
  710 FORMAT(5(/),20X,'FOR EQUATION  A  +  S  *  E  =  DEFLECTION',//)
  720 FORMAT(5(/),23X,'FOR THE EQUATION [B]  *  [E]  =  [C]',//)
  761 FORMAT(80(1H*),/,5X,'DATA FOR DEVELOPING EQUATIONS FOR ITERATIONS',
     &' NO. ',2X,I2)
  760 FORMAT(1H1,5(/),5X,'DATA FOR DEVELOPING EQUATIONS FOR ITERATIONS
     & NO. ',I2,///5X,'LAYER   INITIAL   CHANGED     OFFSET',10X,
     &'DEFLECTIONS',/5X,'NO.',5X,'MODULUS   MODULUS',5X,' DISC.   INITIAL
     &      CHANGED  READINGS',/,72('*'))
  770 FORMAT(6X,I2,4X,F8.0,3X,F8.0,4X,F6.2,3X,F6.3,6X,F6.3,3X,F6.3)
  780 FORMAT(T36,F6.2,3X,F6.3,6X,F6.3,3X,F6.3)
  790 FORMAT(///)
  810 FORMAT(72('*'))
  715 FORMAT(28X,"AVERAGE:",2F10.4)
  840 FORMAT(23X,"ABSOLUTE SUM:",2F10.4,/,22X,
     &"ARITHMETIC SUM:",10X,F10.4)
  850 FORMAT(1H ,26H***** END OF PROGRAM *****)
 1212   FORMAT(1H1,///,"PROBLEM NUMBER ",I4,////)
      END
      SUBROUTINE CHEVRON
CR040     65R040  N-LAYER ELASTIC SYSTEMS PROGRAM
C     CALCULATING STRESSES, STRAINS, AND DEFLECTIONS
C191MN  ****** MAIN ROUTINE - N-LAYER ELASTIC SYSTEM ******
C
      COMMON   /RMCOY/RR(10),    ZZ(10),    E(5),      V(5),      HH(4),
     &                H(4),      AZ(396),   A(396,5),  B(396,5),  C(396,5),
     &                D(396,5),  AJ(396),   RJ1(396),  RJ0(396),  TITLE(20),
     &                TEST(11),  BZ(100),   X(5,4,4),   SC(4),     FM(2,2),
     &                PM(4,4,4),R,          Z,         AR,        NS,
     &                N,         L,         ITN,       RSZ,       RSR,
     &                ROM,       RMU,       SF,        CSZ,       CST,
     &                CSR,       CTR,       COM,       CMU,       PSI,
     &                NLINE,     NOUTP,     NTEST,     I,         ITN4,
     &                K,         LC,        JT,        TZZ,       PR,
     &                PA,        P,         EP,        TIP,       TIM,
     &                T1,        T2,        T3,        T4,        T5,
     &                T6,        T2P,       T2M,       WA,        BJ1,
     &                BJ0,       ZF,        SZ1,       SZ2,       SG1,
     &                SG2,       PH,        PH2,       VK2,       VKP2,
     &                VK4,       VKP4,      VKK8,      RDT,       RDS
       COMMON/OPT/COUNTR,DEF(4),NLAYS
      INTEGER COUNTR
      DATA   ASTER, PERD/4H****, 4H..../
      IF(COUNTR.EQ.99) GO TO 7
      IF(COUNTR.GE.2) GO TO 26
      CALL FLGEOF (41,NFILE)
C
C         ** COMPUTE ZEROS OF J1(X) AND J0(X). SET UP GAUSS CONSTANTS **
      K = ITN+1
      DO 2 I=7,K,2
            T = I/2
            TD = 4.0*T - 1.0
    2       BZ(I) = 3.1415927*(T - 0.25 + 0.050661/TD
     &            -0.053041/TD**3 + 0.262051/TD**5)
      DO 3 I=8,ITN,2
            T = (I-2)/2
```

```
            TD = 4.0*T + 1.0
    3       BZ(I) = 3.1415927*(T + 0.25 - 0.151982/TD
     &          + 0.015399/TD**3 - 0.245270/TD**5)
C
   10 READ(5, 398) TITLE
  398 FORMAT(20A4)
      IF(NFILE.EQ.1) GO TO 9999
  310 FORMAT (20A4)
      READ(5, 399) LINENU, WGT,PSI,NOUTP,NPUN
  311 FORMAT (2F12.0, I12, I1)
      READ(5,399)  LINENU,  NS, (E(I),V(I), I = 1, NS)
      NLAYS = NS
  301 FORMAT(I3,F9.0,9F6.0)
  399 FORMAT(V)
    1 FORMAT(6X,10F6.0)
 1001 CONTINUE
      N = NS - 1
      READ(5, 399) LINENU, (HH(I),I=1,N)
  313 FORMAT (10F6.0)
    7 READ(5, 399) LINENU, IR,(RR(I),I=1,IR)
      IF(IR.EQ.0) RETURN
 2001 CONTINUE
      READ(5, 399) LINENU, IZ,(ZZ(I),I=1,IZ)
      IF(COUNTR.EQ.99) GO TO 26
 3001 CONTINUE
      AP = SQRT (WGT/(3.14159*PSI))
      NLINE = 17+NS
      NPAGE = 1
      WRITE(6,350) (TITLE (I), I=1,20)
  350 FORMAT (1H1//1H0,5H*****,20A4)
      WRITE(6,351)
  351 FORMAT (1H0,23X,26HTHE PROBLEMPARAMETERS ARE//)
      WRITE(6,352) WGT,PSI,AP
  352 FORMAT (1H0, 5X, 12HTOTAL LOAD.., 8X, F10.2, 5H  LBS,/
     %          1H0, 5X, 15HTIRE PRESSURE.., 5X, F10.2, 5H  PSI,/
     %          1H0,5X,13HLOAD RADIUS..,7X,F10.2,5H  IN.//)
      WRITE(6,353)
  353 FORMAT(1H0,5X,9HLAYER NO.,8X,7HMODULUS,8X,14HPOISSONS RATIO,
     %         8X,9HTHICKNESS/)
      WRITE(6,354) (I,E(I), V(I), HH(I), I=1,N)
  354 FORMAT (1H0,8X,I3,9X,F10.0,11X,F5.3,14X,F6.2)
      WRITE(6,349) NS, E(NS), V(NS)
  349 FORMAT (1H0,8X,I3,9X,F10.0,11X,F5.3,11X,14HSEMI-INFINITE ///)
      IF(COUNTR.NE.99) GO TO 27
      WRITE (6,348)
  348 FORMAT (1H ,1X,1HR,3X,1HZ,11X,8HVERTICAL,2X,10HTANGENTIAL,
     &            3X,6HRADIAL,6X,5HSHEAR,6X,4HBULK)
   27 CONTINUE
C  ** ADJUST LAYER DEPTHS **
      H(1)=HH(1)
      DO 25 I=2,N
   25 H(I)=H(I-1)+HH(I)
      CALL CHECK (1)
   26 CONTINUE
      IF(COUNTR.EQ.99) WRITE(6,348)
      IRT=0
C  ** START ON A NEW R **
  100 IRT=IRT+1
      IF (IRT IR) RETURN
  105 R=RR(IRT)
```

```
      DO 31 I =1,IZ
      DO 31 J=1,N
      TZ  = ABS (H(J) - ZZ(I))
      IF(TZ - .0001) 32,32,31
   32 ZZ(I) = -H(J)
   31 CONTINUE
      IF(COUNTR.NE.99) GO TO 39
      WRITE(6, 355)
      NLINE = NLINE+1
  355 FORMAT(1H )
   39 CONTINUE
C  ** CALCULATE THE PARTITION **
      CALL PART
C  ** CALCULATE THE COEFFICIENTS **
      DO 125 I=1,ITN4
      P=AZ(I)
  107 CONTINUE
      IF(NS.GT.5) GOTO 108
      CALL COE5(I)
      GO TO 109
  108 CONTINUE
      CALL CO15(I)
  109   IF (R) 115,115,110
  110   PR = P*R
      CALL BESSEL (0,PR,Y)
          RJ0(I) = Y
      CALL BESSEL (1,PR,Y)
          RJ1(I) = Y
  115 PA=P*AR
      CALL BESSEL (1,PA,Y)
      AJ(I)=Y
      CALL CHECK (2)
  125 CONTINUE
  195 IZT=0
C  ** START ON A NEW Z **
  200 IZT=IZT+1
      IF(IZT-IZ) 205,205,100
  205 Z=ABS (ZZ(IZT))
      IF ( NLINE - 54 ) 207,206,206
  206 NPAGE = NPAGE + 1
      NLINE = 8
  207 CONTINUE
C  ** FIND THE LAYER CONTAINING Z **
      TZZ = 0.0
      DO 210 J1=1,N
      J=NS-J1
      IF(Z-H(J)) 210,215,215
  210 CONTINUE
      L = 1
      GO TO 34
  215 L=J+1
      IF (ZZ(IZT)) 33,34,34
   33 L = J
      TZZ = 1.0
   34 CONTINUE
      CALL CALCIN(IRT)
      IF (TZZ) 36,36,35
   35 ZZ(IZT) = -ZZ(IZT)
      IZT = IZT-1
   36 CONTINUE
```

```
04750         GO TO 200
04760 9999 CALL EXIT
04770         STOP
04780         END
04790         BLOCK DATA
04800C
04810         COMMON    /PMCOY/RR(10),    ZZ(10),    E(5),       V(5),       HH(4),
04820      &                 H(4),        AZ(396),   A(396,5),   B(396,5),   C(396,5),
04830      &                 D(396,5),    AJ(396),   RJ1(396),   RJ0(396),   TITLE(20),
04840      &                 TEST(11),    BZ(100),   X(5,4,4),   SC(4),      FM(2,2),
04850      &                 PM(4,4,4),P,            Z,          AR,         NS,
04860      &                 N,           L,         ITN,        RSZ,        RSR,
04870      &                 ROM,         RMU,       SF,         CSZ,        CST,
04880      &                 CSR,         CTR,       COM,        CMU,        PSI,
04890      &                 NLINE,       NOUTP,     NTEST,      I,          ITN4,
04900      &                 K,           LC,        JT,         TZZ,        PR,
04910      &                 PA,          P,         EP,         TIP,        TIM,
04920      &                 T1,          T2,        T3,         T4,         T5,
04930      &                 T6,          T2P,       T2M,        WA,         BJ1,
04940      &                 BJ0,         ZF,        SZ1,        SZ2,        SG1,
04950      &                 SG2,         PH,        PH2,        VK2,        VKP2,
04960      &                 VK4,         VKP4,      VKK8,       RDT,        RDS
04970         DIMENSION ZB(6)
04980         EQUIVALENCE (BZ,ZB )
04990         DATA ZB/0.0,1.0,2.4048,3.8317,5.5201,7.0156/
05000         DATA ITN/46/,ITN4/184/
05010         END
05020         SUBROUTINE BESSEL(NI,XI,Y)
05030C          ******SUBROUTINE BESSEL - N-LAYER ELASTIC SYSTEM ******
05040C
05050         DIMENSION PZ(6),QZ(6),P1(6),Q1(6),D(20)
05060         DATA PZ/1.0E0,-1.125E-4,2.8710938E-7,-2.3449658E-9,
05070        &3.9806841E-11,-1.1536133E-12/,  QZ/-5.0E-3,4.6875E-6,
05080        &-2.3255859E-8, 2.8307087E-10, -6.3912096E-12,  2.3124704E-12/,
05090        &P1/ 1.0E0,  1.875E-4,       -3.6914063E-7,   2.7713232E-9,
05100        &-4.5114421E-11,1.2750463E-12/, Q1/1.5E-2,  -6.5625E-6,
05110        & 2.8423828E-8,-3.2662024E-10,  7.1431166E-12, -2.5327056E-13/,
05120        & PI/3.1415927/
05130C
05140C
05150       9 N = NI
05160         X = XI
05170         IF (X-7.0) 10,10,160
05180C
05190      10 X2=X/2.0
05200         FAC=-X2*X2
05210         IF (N) 11,11,14
05220      11 C=1.0
05230         Y=C
05240         DO 13 I=1,34
05250         T=I
05260         C=FAC*C/(T*T)
05270         TEST=ABS (C) - 10.0**(-8)
05280         IF (TEST) 17,17,12
05290      12 Y=Y+C
05300      13 CONTINUE
05310      14 C=X2
05320         Y=C
05330         DO 16 I=1,34
05340         T=I
```

```
05350        C=FAC*C/(T*(T+1.0))
05360        TEST=ABS (C) - 10.0**(-8)
05370        IF (TEST) 17,17,15
05380    15  Y=Y+C
05390    16  CONTINUE
05400    17  RETURN
05410   160  IF (N) 161,161,164
05420C
05430C
05440   161  DO 162 I=1,6
05450        D(I) = PZ(I)
05460        D(I+10) = QZ(I)
05470   162  CONTINUE
05480        GO TO 163
05490C
05500   164  DO 165 I=1,6
05510        D(I) = P1(I)
05520        D(I+10) = Q1(I)
05530   165  CONTINUE
05540   163  CONTINUE
05550        T1 = 25.0/X
05560        T2=T1*T1
05570        P = D(6)*T2+D(5)
05580        DO 170 I=1,4
05590        J = 5-I
05600        P = P*T2+D(J)
05610   170  CONTINUE
05620        Q = D(16)*T2+D(15)
05630        DO 171 I=1,4
05640        J = 5-I
05650        Q = Q*T2+D(J+10)
05660   171  CONTINUE
05670        Q = Q*T1
05680C
05690        T4 =DSQRT (X*PI)
05700        T6 = SIN (X)
05710        T7 = COS (X)
05720C
05730        IF (N) 180,180,185
05740C
05750   180  T5 = ((P-Q)*T6 + (P+Q)*T7)/T4
05760        GO TO 99
05770   185  T5 = ((P+Q)*T6 - (P-Q)*T7)/T4
05780    99  Y = T5
05790        RETURN
05800        END
05810        SUBROUTINE PART
05820C        ******SUBROUTINE PART - N-LAYER ELASTIC SYSTEM ******
05830C
05840        COMMON   /RMCOY/RR(10),   ZZ(10),    E(5),      V(5),      HH(4),
05850     &                 H(4),      AZ(396),   A(396,5),  B(396,5),  C(396,5),
05860     &                 D(396,5),  AJ(396),   RJ1(396),  RJ0(396),  TITLE(20),
05870     &                 TEST(11),  BZ(100),   X(5,4,4),  SC(4),     FM(2,2),
05880     &                 PM(4,4,4),R,          Z,         AR,       NS,
05890     &                 N,         L,         ITN,       RSZ,       RSR,
05900     &                 ROM,       RMU,       SF,        CSZ,       CST,
05910     &                 CSR,       CTR,       COM,       CMU,       PSI,
05920     &                 NLINE,     NOUTP,     NTEST,     I,         ITN4,
05930     &                 K,         LC,        JT,        TZZ,       PR,
05940     &                 PA,        P,         EP,        TIP,       TIM,
```

```
     &                  T1,       T2,       T3,       T4,       T5,
     &                  T6,       T2P,      T2M,      WH,       BJ1,
     &                  BJ0,      ZF,       SZ1,      SZ2,      SG1,
     &                  SG2,      PH,       PH2,      VK2,      VKP2,
     &                  VK4,      VKP4,     VKK8,     RDT,      RDS
      DATA   G1/0.86113631/,G2/0.33998104/
    4 ZF = AR
      NTEST = 2
      IF (R) 8,8,9
    9 CONTINUE
      NTEST = AR/R + .0001
      IF (NTEST) 6,6,5
    6 CONTINUE
      NTEST = R/AR + .0001
      ZF = R
    5 CONTINUE
      NTEST = NTEST + 1
      IF (NTEST-10) 8,8,7
    7 CONTINUE
      NTEST = 10
    8 CONTINUE
C        ** COMPUTE POINTS FOR LEGENDRE-GAUSS INTEGRATION **
   15 K = 1
      CALL CHECK (9)
       ZF = 2.0*ZF
       SZ2 = 0.0
      DO 28 I=1,ITN
        SZ1 = SZ2
        SZ2 = BZ(I+1)/ZF
           SF = SZ2 - SZ1
           PP = SZ2 + SZ1
      SG1=SF*G1
      SG2=SF*G2
      AZ(K)=PP-SG1
      AZ(K+1)=PP-SG2
      AZ(K+2)=PP+SG2
      AZ(K+3)=PP+SG1
         K = K + 4
      CALL CHECK (10)
   28 CONTINUE
   40 RETURN
      END
      SUBROUTINE CALCIN(IRT)
C     ******SUBROUTINE CALCIN - N-LAYER ELASTIC SYSTEM ******
C
      COMMON   /RMCOY/RR(10),   ZZ(10),   E(5),     V(5),     HH(4),
     &                  H(4),     AZ(396),  A(396,5), B(396,5), C(396,5),
     &                  D(396,5), AJ(396),  RJ1(396), RJ0(396), TITLE(20),
     &                  TEST(11), BZ(100),  X(5,4,4), SC(4),    FM(2,2),
     &                  PM(4,4,4),R,        Z,        AR,       NS,
     &                  N,        L,        ITN,      RSZ,      RSR,
     &                  POM,      RMU,      SF,       CSZ,      CST,
     &                  CSR,      CTR,      COM,      CMU,      PSI,
     &                  NLINE,    NOUTP,    NTEST,    I,        ITN4,
     &                  K,        LC,       JT,       TZZ,      PR,
     &                  PA,       P,        EP,       TIP,      TIM,
     &                  T1,       T2,       T3,       T4,       T5,
     &                  T6,       T2P,      T2M,      WA,       BJ1,
     &                  BJ0,      ZF,       SZ1,      SZ2,      SG1,
     &                  SG2,      PH,       PH2,      VK2,      VKP2,
```

```
     &                   VK4,      VKP4,     VKK8,     PDT,      PD
      COMMON/OPT/COUNTR,DEF(4),NLAYS
      INTEGER COUNTR
      DIMENSION W(4)
      DATA W/0.34785485,2*0.65214515,0.34785485/
C
    2 VL=2.0*V(L)
      EL=(1.0+V(L))/E(L)
      VL1=1.0-VL
      CSZ=0.0
      CST=0.0
      CSR=0.0
      CTR=0.0
      COM=0.0
      CMU=0.0
      NTS1 = NTEST + 1
      ITS = 1
      JT = 0
      ARP = AR
      IF (NOUTP) 4,4,5
    4 ARP = ARP*PSI
    5 CONTINUE
   10 DO 40 I=1,ITN
C     INITIALIZE THE SUB-INTEGRALS
      RSZ=0.0
      RST=0.0
      RSR=0.0
      RTR=0.0
      ROM=0.0
      RMU=0.0
C     COMPUTE THE SUB-INTEGRALS
          K = 4*(I-1)
      DO 30 J=1,4
          J1 = K + J
      P=AZ(J1)
      EP=EXP (P*Z)
      T1=B(J1,L)*EP
      T2=D(J1,L)/EP
      T1P=T1+T2
      T1M=T1-T2
      T1=(A(J1,L)+B(J1,L)*Z)*EP
      T2=(C(J1,L)+D(J1,L)*Z)/EP
      T2P=P*(T1+T2)
      T2M=P*(T1-T2)
      WA=AJ(J1)*W(J)
      CALL CHECK (3)
      IF (R) 20,20,15
   15 BJ1=RJ1(J1)*P
      BJ0=RJ0(J1)*P
      RSZ=RSZ+WA*P*BJ0*(VL1*T1P-T2M)
      ROM=ROM+WA*EL*BJ0*(2.0*VL1*T1M-T2P)
      RTR=RTR+WA*P*BJ1*(VL*T1M+T2P)
      RMU=RMU+WA*EL*BJ1*(T1P+T2M)
      RSR=RSR+WA*(P*BJ0*((1.0+VL)*T1P+T2M)-BJ1*(T1P+T2M)/R)
      RST=RST+WA*(VL*P*BJ0*T1P+BJ1*(T1P+T2M)/R)
      CALL CHECK (4)
      GO TO 30
C     SPECIAL ROUTINE FOR R = ZERO
   20 PP=P*P
      RSZ=RSZ+WA*PP*(VL1*T1P-T2M)
```

```
      ROM=ROM+WA*EL*P*(2.0*VL1*T1M-T2P)
      RST=RST+WA*RP*((VL+0.5)*T1P+0.5*T2M)
      RSR=RST
      CALL CHECK (5)
   30 CONTINUE
C
       SF = (AZ(K+4) - AZ(K+1))/1.7222726
      CSZ=CSZ+RSZ*SF
      CST=CST+RST*SF
      CSR=CSR+RSR*SF
      CTR=CTR+RTR*SF
      COM=COM+ROM*SF
      CMU=CMU+RMU*SF
          RSZ = 2.0*RSZ*AR*SF
      CALL CHECK (6)
      TESTH = ABS (RSZ)-10.0**(-4)
      IF (ITS-NTS1 ) 31,32,32
   31 CONTINUE
      TEST(ITS) = TESTH
      ITS = ITS+1
      GO TO 40
   32 CONTINUE
      TEST(NTS1) = TESTH
      DO 33 J = 1,NTEST
      IF (TESTH-TEST(J)) 35,36,36
   35 CONTINUE
      TESTH = TEST(J)
   36 CONTINUE
      TEST(J) = TEST(J+1)
   33 CONTINUE
      IF (TESTH) 50,50,40
   40 CONTINUE
      JT = 1
      CALL HIGHM
   50 CSZ=CSZ*APP
      CALL CHECK (7)
      CST=CST*APP
      CTR=CTR*APP
      CSR=CSR*APP
      COM=COM*APP
      IF(COUNTR.NE.99)DEF(IRT)=COM*1000.
      CMU=CMU*APP
      BSTS = CSZ+CST+CSR
      VSTR = (CSZ-V(L)*(CST+CSR))/E(L)
      BST  = BSTS * (1.0-2.0*V(L))/E(L)
      IF (TZZ) 72,72,71
   71 Z = -Z
   72 CONTINUE
      RDS=(CSR-V(L)*(CSZ+CST))/E(L)
      SST=2.0*(1.0+V(L))*CTR/E(L)
      RDT = (CST - V(L) * (CSZ + CSR))/E(L)
      IF(COUNTR.NE.99) GO TO 99
      WRITE (6,315) R,Z,CSZ,CST,CSR,CTR,BSTS
      WRITE (6,318) VSTR,RDT,RDS,SST,BST
      WRITE (6,317) COM
  315 FORMAT (1H0,F4.1,F6.1,1X,5HSTRE ,1P5E11.3)
  318 FORMAT (1H ,11X,5HSTRA ,1P5E11.3)
  317 FORMAT (1H ,11X,5HDSPL ,1PE11.3)
      NLINE = NLINE + 3
      IF (JT) 99,99,60
```

```
07750    60 WRITE(6,316)
07760   316 FORMAT (1H+,127X,4HSLOW)
07770    99 RETURN
07780       END
07790       SUBROUTINE HIGHM
07800C+ *        ******SUBROUTINE HIGHM - N-LAYER ELASTIC SYSTEM ******
07810C      OCTAL LIST
07820C      LABEL
07830CHIGHM  ******SUBROUTINE HIGHM - N-LAYER ELASTIC SYSTEM ******
07840C
07850       RETURN
07860       END
07870       SUBROUTINE CHECK(KIN)
07880C   + *        ******SUBROUTINE CHECK - N-LAYER ELASTIC SYSTEM ******
07890C
07900       COMMON   /PMCOY/RR(10),    ZZ(10),    E(5),      V(5),      HH(4),
07910     &                H(4),       AZ(396),   A(396,5),  B(396,5),  C(396,5),
07920     &                D(396,5),   AJ(396),   RJ1(396),  RJ0(396),  TITLE(20),
07930     &                TEST(11),   BZ(100),   X(5,4,4),  SC(4),     FM(2,2),
07940     &                PM(4,4,4),R,           Z,         AR,        NS,
07950     &                N,          L,         ITN,       RSZ,       RSR,
07960     &                ROM,        RMU,       SF,        CSZ,       CST,
07970     &                CSR,        CTR,       COM,       CMU,       PSI,
07980     &                NLINE,      NOUTP,     NTEST,     I,         ITN4,
07990     &                K,          LC,        JT,        TZZ,       PP,
08000     &                PA,         P,         EP,        TIP,       TIM,
08010     &                T1,         T2,        T3,        T4,        T5,
08020     &                T6,         T2P,       T2M,       WA,        BJ1,
08030     &                BJ0,        ZF,        SZ1,       SZ2,       SG1,
08040     &                SG2,        PH,        PH2,       VK2,       VKP2,
08050     &                VK4,        VKP4,      VKK8,      RDT,       RDS
08060       RETURN
08070       END
08080       SUBROUTINE COFE(KIN)
08090C         USE FOR ALL PROBLEMS, UP TO MAX DIMENSION OF 15 LAYERS
08100C      REPROGRAMMED 1 MAY 1980 BY L J PAINTER - EXCELLENT ACCURACY
08110C        NOTE DOUBLE ENTRIES FOR COE5 & CO15 PREVIOUSLY USED
08120C        ******SUBROUTINE COEE - N-LAYER ELASTIC SYSTEM ******
08130C
08140       COMMON   /PMCOY/RR(10),    ZZ(10),    E(5),      V(5),      HH(4),
08150     &                H(4),       AZ(396),   A(396,5),  B(396,5),  C(396,5),
08160     &                D(396,5),   AJ(396),   RJ1(396),  RJ0(396),  TITLE(20),
08170     &                TEST(11),   BZ(100),   X(5,4,4),  SC(4),     FM(4),
08180     &                PM(4,4,4),R,           Z,         AR,        NS,
08190     &                N,          L,         ITN,       RSZ,       RSR,
08200     &                ROM,        RMU,       SF,        CSZ,       CST,
08210     &                CSR,        CTR,       COM,       CMU,       PSI,
08220     &                NLINE,      NOUTP,     NTEST,     I,         ITN4,
08230     &                K,          LC,        JT,        TZZ,       PP,
08240     &                PA,         P,         EP,        TIP,       TIM,
08250     &                T1,         T2,        T3,        T4,        T5,
08260     &                T6,         T2P,       T2M,       WA,        BJ1,
08270     &                BJ0,        ZF,        SZ1,       SZ2,       SG1,
08280     &                SG2,        PH,        PH2,       VK2,       VKP2,
08290     &                VK4,        VKP4,      VKK8,      RDT,       RDS
08300       REAL*4 O(2,2)
08310       ENTRY  COE5(KIN)
08320       ENTRY  CO15(KIN)
08330          LC = KIN
08340CS-MX           SET UP MATRIX X =DI*MI*KI*K*M*D
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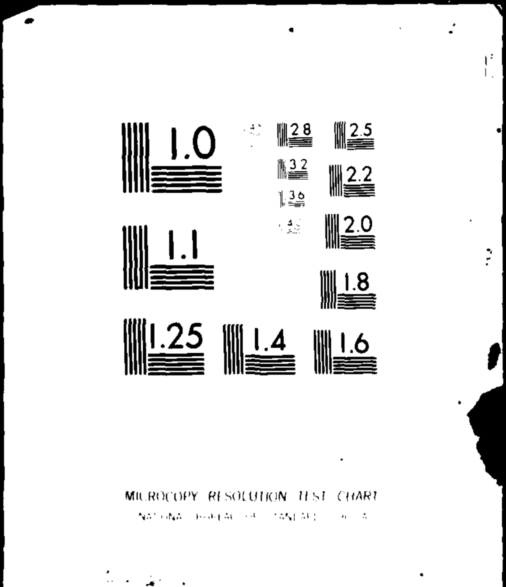
```
08350C      COMPUTE THE MATRICES X(K)
08360     1 DO 10 K=1,N
08370       T1=E(K)◆(1.0+V(K+1))/(E(K+1)◆(1.0+V(K)))
08380       T1M=T1-1.0
08390       PH=P◆H(K)
08400       PH2=PH◆2.0
08410       VK2=2.0◆V(K)
08420       VKP2=2.0◆V(K+1)
08430C
08440       VKK8=8.0◆V(K)◆V(K+1)
08450       VKP4=2.0◆VKP2
08460       VK4=2.0◆VK2
08470       X(K,1,1)=VK4-3.0-T1
08480       X(K,2,1)=0.0
08490       X(K,3,1)=T1M◆(PH2-VK4+1.0)
08500       X(K,4,1)=-2.0◆T1M◆P
08510C
08520       T3=PH2◆(VK2-1.0)
08530       T4=VKK8+1.0-3.0◆VKP2
08540       T5=PH2◆(VKP2-1.0)
08550       T6=VKK8+1.0-3.0◆VK2
08560C
08570       X(K,1,2)=(T3+T4-T1◆(T5+T6))/P
08580       X(K,2,2)=T1◆(VKP4-3.0)-1.0
08590       X(K,4,2)=T1M◆(1.0-PH2-VKP4)
08600C
08610       X(K,3,4)=(T3-T4-T1◆(T5-T6))/P
08620C
08630       T3=PH2◆PH-VKK8+1.0
08640       T4=PH2◆(VK2-VKP2)
08650C
08660       X(K,1,4)=(T3+T4+VKP2-T1◆(T3+T4+VK2))/P
08670       X(K,3,2)=    (-T3+T4-VKP2+T1◆(T3-T4+VK2))/P
08680C
08690       X(K,1,3)=T1M◆(1.0-PH2-VK4)
08700       X(K,2,3)=2.0◆T1M◆P
08710       X(K,3,3)=VK4-3.0-T1
08720       X(K,4,3)=0.0
08730C
08740       X(K,2,4)=T1M◆(PH2-VKP4+1.0)
08750       X(K,4,4)=T1◆(VKP4-3.0)-1.0
08760C      K = K
08770    10 CONTINUE
08780C      COMPUTE THE PRODUCT MATRICES PM
08790       SC(N)=4.0◆(V(N)-1.0)
08800       IF (N-2) 13,11,11
08810    11 DO 12 K1=2,N
08820       M=NS-K1
08830       SC(M)=SC(M+1)◆4.◆(V(M)-1.)
08840    12 CONTINUE
08850    13 CONTINUE
08860C
08870       Q(1,1)=1.
08880       Q(2,2)=1.
08890       Q(1,2)=0.
08900       QQ     =P◆2.◆H(N)
08910       IF(QQ.LT.-88.) QQ=-88.
08920       IF (QQ-88. ) 15,15,16
08930    15 CONTINUE
08940       Q(1,2)=EXP(-QQ)
```

AD-A099 593 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/G 13/2
NONDESTRUCTIVEE TESTING FOR LIGHT AIRCRAFT PAVEMENTS. PHASE II.--ETC(U)
NOV 80 A J BUSH DOT-FA78WAI-848
UNCLASSIFIED FAA-RD-80-9-2 NL

2 of 2
AD A
099 593

2 OF 2

AD A
099593



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

```
C      Q(2,1) IS NOT NEEDED FOR INITIALIZING THE PM MATRIX
    16 CONTINUE
C      20 LOOP INITIALIZES PM(N,,)
       DO 20 M=1,4
       LL=(M+1)/2
       DO 20 J=3,4
       PM(N,M,J)= X(N,M,J) *     Q(LL,2)
    20 CONTINUE
       DO 26 K1=2,N
       K=NS-K1
       KK=K+1
       QQ     =P*2.*H(K)
       IF(QQ.LT.-88.) QQ=-88.
       IF (QQ-88. ) 22,22,23
    22 CONTINUE
       Q(2,1)=EXP(QQ)
       Q(1,2)=1./Q(2,1)
       GO TO 24
    23 CONTINUE
       Q(1,2)=0.
       Q(2,1)=1.E20
    24 CONTINUE
       DO 25 M=1,4
       LL=(M+1)/2
       DO 25 J=3,4
       PM(K,M,J)=( X(K,M,1) * PM(KK,1,J)
     &            +X(K,M,2) * PM(KK,2,J) ) * Q(LL,1)
     &          +( X(K,M,3) * PM(KK,3,J)
     &            +X(K,M,4) * PM(KK,4,J) ) * Q(LL,2)
    25 CONTINUE
    26 CONTINUE
C      SOLVE FOR C(NS) AND D(NS)

       T3=2.0*V(1)
       T4 =T3-1.0

       FM(1)= P*(PM(1,1,3)+PM(1,3,3)) + T3*(PM(1,2,3)-PM(1,4,3))
       FM(2)= P*(PM(1,1,3)-PM(1,3,3)) + T4*(PM(1,2,3)+PM(1,4,3))
       FM(3)= P*(PM(1,1,4)+PM(1,3,4)) + T3*(PM(1,2,4)-PM(1,4,4))
       FM(4)= P*(PM(1,1,4)-PM(1,3,4)) + T4*(PM(1,2,4)+PM(1,4,4))
       DFAC=SC(1)/((FM(1)*FM(4)-FM(3)*FM(2))*P*P)
          A(LC,NS) = 0.0
          B(LC,NS) = 0.0
          C(LC,NS) = -FM(3)*DFAC
           D(LC,NS) = FM(1)*DFAC
C      BACKSOLVE FOR THE OTHER A,B,C,D
       DO 91 K1=1,N
       A(LC,K1)=(PM(K1,1,3)*C(LC,NS)+PM(K1,1,4)*D(LC,NS))/SC(K1)
       B(LC,K1)=(PM(K1,2,3)*C(LC,NS)+PM(K1,2,4)*D(LC,NS))/SC(K1)
       C(LC,K1)=(PM(K1,3,3)*C(LC,NS)+PM(K1,3,4)*D(LC,NS))/SC(K1)
    91 D(LC,K1)=(PM(K1,4,3)*C(LC,NS)+PM(K1,4,4)*D(LC,NS))/SC(K1)
   100 CONTINUE
       RETURN
       END
       SUBROUTINE SIMEQ (A,B,N,KERR,IDIM)
C      SIMEQ
C:      THIS SUBROUTINE SOLVES A SYSTEM OF LINEAR EQUATIONS
C:      AX=B BY THE METHOD OF PIVOTAL CONDENSATION.IT IS USED
C:      FOR DENSE MATRICES OF COEFFICIENTS.
C:      CALLING ARGUMENTS:
C:      A: THE NAME OF AN N BY N MATRIX OF COEFFICIENTS OF THE EQUATIONS
C:              WHICH IS DESTROYED DURING COMPUTATION.
```

```
09570C:      B: THE NAME OF AN ARRAY CONTAINING THE N CONSTANTS.
09580C:      N: THE ORDER OF THE SYSTEM
09590C:      KERR: INDICATOR RETURNED BY THE SUBROUTINE WHICH IS
09600C:              ONE IF SYSTEM IS SINGULAR AND ZERO OTHERWISE.
09610C:            READ A COLUMN BY COLUMN.
09620C:
09630       DIMENSION A(IDIM,IDIM),B(IDIM),L(50),M(50)
09640        EPS=1E-6
09650        EPSQR=EPS*EPS
09660        KERR=0
09670C:      CLEAR OUT PERMUTATION VECTORS
09680        DO 3 I=1,N
09690          M(I)=0
09700 3       L(I)=0
09710C:      LOOP FOR N PIVOT POINTS
09720         DO 14 KP=1,N
09730         P=0.
09740         PSQR=0.
09750         DO 7 I=1,N
09760         DO 7 J=1,N
09770         IF(M(I))7,4,7
09780 4       IF(L(J))7,5,7
09790 5       T=A(I,J)
09800         TSQR=T*T
09810        IF (TSQR-PSQR)7,7,6
09820 6       P=T
09830         PSQR=TSQR
09840         KR=I
09850         KC=J
09860 7       CONTINUE
09870         IF (PSQR-EPSQR)17,17,8
09880 8       M(KR)=KC
09890         L(KC)=1
09900C:      DIVIDE KEY ROW BY PIVOT
09910        DO 30 J=1,N
09920         IF(L(J))30,9,30
09930 9       A(KR,J)=A(KR,J)/P
09940 30      CONTINUE
09950         BKR=B(KR)/P
09960         B(KR)=BKR
09970C:      SUBTRACT MULTIPLE OF KEY ROW FROM OTHER ROWS
09980         DO 14 I=1,N
09990         IF (I-KR)31,14,31
10000 31      R=A(I,KC)
10010        DO 33 J=1,N
10020         IF (L(J)) 33,32,33
10030 32      A(I,J)=A(I,J)-R*A(KR,J)
10040 33      CONTINUE
10050         B(I)=B(I)-R*BKR
10060 14      CONTINUE
10070C:      REORDER RESULTS
10080         DO 35 I=1,N
10090         IP=M(I)
10100 35      A(IP,1)=B(I)
10110        DO 36 I=1,N
10120 36      B(I)=A(I,1)
10130         RETURN
10140C:      ERROR ACTION
10150 17      KERR=1
10160         RETURN
10170         END

READY

*
```

APPENDIX C: GUIDE TO USE OF COMPUTER PROGRAM PAVEVAL

The computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness for rigid and flexible pavements. A program listing is contained in the report by Weiss.[3] Input guides, typical inputs, and typical outputs are furnished in this appendix for evaluation of load-carrying capability of both flexible and rigid pavements.

INPUT GUIDE FOR FLEXIBLE PAVEMENTS

Line 1

Title	80 characters

Line 2

NSYS

NSYS = Number of problems to run

Line 3

EKEY	EKEY2

EKEY = Limiting strain and stress subroutine code: set = 2, for calls to subroutine flex

EKEY2 = Pavement problem code: set = 0, for allowable load

Line 4

ES	EA	YRN	ALOAD	ALIN	CAREA	DSM	SWL	PCRATIO

ES = Subgrade modulus, psi

EA = Asphalt modulus of existing layer

YRN = Yearly load repetition number

ALOAD = Initial load, lb

ALIN = Load increment, lb

CAREA = Contact area (πr^2), $in.^2$

DSM = Dynamic stiffness modulus, for reference only (any number)

SWL = Set = 0

PCRATIO = Pass-to-coverage ratio

Line 5

NLAYS	ISMO	IRED

NLAYS = Number of layers in pavement system

ISMO = Request for rough computational procedure: set = 0

IRED = Input format for Line 6: set = 0

Line 6-1 through 6-(NLAYS-1) (one for each layer, except last layer)

E(i)	NU(i)	THICK(i)	AK(i)

E(i) = Modulus of layer i

NU(i) = Poisson's ratio of layer i

THICK(i) = Thickness of layer i

AK(i) = Interface compliance: set all AK(i)'s = 0

Line 7

E(NLAYS)	NU(NLAYS

E(NLAYS) = Modulus of last layer

NU(NLAYS) = Poisson's ratio of last layer

Line 8

NLOAD

NLOAD = Number of loaded areas

Line 9 (one for each load)

LOSTRS(i)	RADIUS(i)	X(i)	Y(i)	HOSTR(i)	PSI(i)

LOSTRS(i) = Vertical load for load area i

RADIUS(i) = Radius of loaded area i

X(i) = Abscissa of center of loaded area: set = 0

Y(i) = Ordinate of center of loaded area: set = 0

HOSTR(I) = Horizontal load for load area i: normally = 0

PSI(i) = Angle of HOSTR(i) with respect to positive X-axis in in degrees: normally = 0

Line 10

NPOS

NPOS = Number of depths that will be used for iteration purposes: set = 2

Line 11-1 through 11-NPOS

LAYER(I)	AX(i)	AY(i)	DEPTH(i)	ETA(i)

LAYER(i) = Layer number for position i: set; LAYER(1) = 1, Layer(1) = NLAYS(last layer)

AX(i) = Abscissa of position: set AX(1) = AX(2) = 0

AY(i) = Ordinate of position: set AY(1) = AY(2) = 0

DEPTH(i) = Depth from pavement surface to position: set; DEPTH(1) = THICK(1), DEPTH(2) = distance from pavement surface to top of subgrade

ETA(i) = Angle from which position is observed: set = 0

TYPICAL INPUT FOR FLEXIBLE PAVEMENT EVALUATION

```
010##N
020$:IDENT:R0IF300,BUSH
030$:OPTION:FORTRAN
040$:MIG3:060480/1700
050$:USE:.GTLIT
060$:FORTY:XREF
070$:SELECTA:PAVEVAL
080$:NOTE:PAVEVAL
090$:EXECUTE
100$:LIMITS:30,30K,,15000
110PTRF 1A 20 KIP SINGLE                             LINE 1
120  1                                               LINE 2
130  2 0                                             LINE 3
140  8320 770000 25000 20000 1000 127 1000 0 7.94 LINE 4
150  3 0 0                                           LINE 5
160  770000 0.35  7.5 0                              LINE 6-1
170  40304  0.35 20.5 0                              LINE 6-2
180  8320   0.40                                     LINE 7
190  1                                               LINE 8
200  9500 6.36 0 0 0 0                               LINE 9
210  2                                               LINE 10
220  1 0 0 7.5 0                                     LINE 11-1
230  3 0 0 22. 0                                     LINE 11-2
240$:ENDJOB
```

TYPICAL OUTPUT FOR FLEXIBLE PAVEMENT EVALUATION

```
* * * * * F L E X I B L E   P A V E M E N T   A L L O W A B L E   L O A D * * * *

**************************************************************************
STRL(SUBGRADE LIMITING STRAIN) =        0.00085465
STRL2(ASPHALT LIMITING STRAIN) =        0.00027464
ALOAD =            20000.
ALIN =             1000.
**************************************************************************


                                SYSTEM NUMBER    1

 LAYER    CALCULATION  YOUNG'S     POISSON'S    THICKNESS    INTERFACE
 NUMBER   METHOD       MODULUS     RATIO                     SPRINGCOMPL
    1     ROUGH      0.7700E 06  0.3500E 00   0.7500E 01   0.
    2     ROUGH      0.4030E 05  0.3500E 00   0.2050E 02   0.
    3                0.8320E 04  0.4000E 00


 LOAD     NORMAL        SHEAR      RADIUS OF      LOAD - POSITION        SHEAR
 NUMBER   STRESS        STRESS     LOADED AREA      X            Y       DIRECTION
    1    0.1574E 03   0.           0.6360E 01   0.           0.          0.
```

```
                                              POSITION NUMBER  1

                                               LAYER NUMBER   1

                                                COORDINATES

                                          X            Y           Z
                                     0.           0.          0.7500E 01

               DISTANCE TO LOAD-AXIS( 1)                                          THETA
                     0.                                                           0.
 DISPLACEMENTS
    RADIAL           TANGENTIAL          VERTICAL
  0.                  0.                 0.2994E-01
   STRESSES
    RADIAL           TANGENTIAL          VERTICAL           RAD./TANG.            RAD./VERT.            TANG./VERT.
  0.2458E 03          0.2458E 03        -0.2587E 02          0.                    0.                    0.
   STRAINS
    RADIAL           TANGENTIAL          VERTICAL           RAD./TANG.            RAD./VERT.            TANG./VERT.
  0.2193E-03          0.2193E-03        -0.2571E-03          0.                    0.                    0.
MAXIMUM NORMAL STRAIN =      0.00021928        0.                0.             7.50


                                              POSITION NUMBER  2

                                               LAYER NUMBER   3

                                                COORDINATES

                                          X            Y           Z
                                     0.           0.          0.2000E 02

               DISTANCE TO LOAD-AXIS( 1)                                          THETA
                     0.                                                           0.
 DISPLACEMENTS
    RADIAL           TANGENTIAL          VERTICAL
  0.                  0.                 0.2133E-01
   STRESSES
    RADIAL           TANGENTIAL          VERTICAL           RAD./TANG.            RAD./VERT.            TANG./VERT.
  0.7656E-01          0.7656E-01        -0.3367E 01          0.                    0.                    0.
   STRAINS
    RADIAL           TANGENTIAL          VERTICAL           RAD./TANG.            RAD./VERT.            TANG./VERT.
  0.1674E-03          0.1574E-03        -0.4120E-03          0.                    0.                    0.
VERTICAL STRAIN =   -0.00041205       0.                0.              20.00
```

```
                                                POSITION NUMBER  1

                                                 LAYER NUMBER   1

                                                  COORDINATES

                                         X              Y              Z
                                      0.             0.         0.7500E 01

                        DISTANCE TO LOAD-AXIS( 1)                                      THETA
                              0.                                                       0.
 DISPLACEMENTS
   RADIAL               TANGENTIAL               VERTICAL
  0.                      0.                     0.2836E-01
   STRESSES
    RADIAL              TANGENTIAL               VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.2583E 03              0.2583E 03            -0.2718E 02            0.                  0.                  0.
   STRAINS
    RADIAL              TANGENTIAL               VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.2304E-03              0.2304E-03            -0.2701E-03            0.                  0.                  0.
MAXIMUM NORMAL STRAIN =        0.00023039          0.               0.             7.50



                                                POSITION NUMBER  2

                                                 LAYER NUMBER   3

                                                  COORDINATES

                                         X              Y              Z
                                      0.             0.         0.2800E 02

                        DISTANCE TO LOAD-AXIS( 1)                                      THETA
                              0.                                                       0.
 DISPLACEMENTS
   RADIAL               TANGENTIAL               VERTICAL
  0.                      0.                     0.2241E-01
   STRESSES
    RADIAL              TANGENTIAL               VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.8043E-01              0.8043E-01            -0.3537E 01            0.                  0.                  0.
   STRAINS
    RADIAL              TANGENTIAL               VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.1759E-03              0.1759E-03            -0.4329E-03            0.                  0.                  0.
VERTICAL STRAIN =     -0.00043291          0.               0.           28.00
```

```
                                          POSITION NUMBER  1

                                           LAYER NUMBER   1

                                            COORDINATES

                                      X           Y          Z
                                   0.          0.        0.7500E 01

                  DISTANCE TO LOAD-AXIS( 1)                                THETA
                        0.                                                 0.
DISPLACEMENTS
  RADIAL             TANGENTIAL          VERTICAL
 0.                   0.                 0.3076E-01
  STRESSES
  RADIAL             TANGENTIAL          VERTICAL         RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.2706E 03           0.2706E 03        -0.2847E 02        0.                  0.                  0.
  STRAINS
  RADIAL             TANGENTIAL          VERTICAL         RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.2414E-03           0.2414E-03        -0.2830E-03        0.                  0.                  0.
MAXIMUM NORMAL STRAIN =     0.00024136         0.             0.             7.50


                                          POSITION NUMBER  2

                                           LAYER NUMBER   3

                                            COORDINATES

                                      X           Y          Z
                                   0.          0.        0.2800E 02

                  DISTANCE TO LOAD-AXIS( 1)                                THETA
                        0.                                                 0.
DISPLACEMENTS
  RADIAL             TANGENTIAL          VERTICAL
 0.                   0.                 0.2347E-01
  STRESSES
  RADIAL             TANGENTIAL          VERTICAL         RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.8426E-01           0.8426E-01        -0.3706E 01        0.                  0.                  0.
  STRAINS
  RADIAL             TANGENTIAL          VERTICAL         RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.1842E-03           0.1842E-03        -0.4835E-03        0.                  0.                  0.
VERTICAL STRAIN =   -0.00045352        0.            0.          28.00
```

```
                                                        POSITION NUMBER  1

                                                         LAYER NUMBER   1

                                                          COORDINATES

                                                 X             Y              Z
                                            0.             0.           0.7500E 01

                     DISTANCE TO LOAD-AXIS( 1)                                              THETA
                             0.                                                             0.
  DISPLACEMENTS
     RADIAL              TANGENTIAL              VERTICAL
    0.                    0.                     0.3215E-01
    STRESSES
     RADIAL              TANGENTIAL              VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
    0.2829E 03            0.2829E 03            -0.2976E 02            0.                  0.                  0.
    STRAINS
     RADIAL              TANGENTIAL              VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
    0.2523E-03            0.2523E-03            -0.2858E-03            0.                  0.                  0.
MAXIMUM NORMAL STRAIN =       0.00025233          0.               0.              7.50


                                                        POSITION NUMBER  2

                                                         LAYER NUMBER   3

                                                          COORDINATES

                                                 X             Y              Z
                                            0.             0.           0.2800E 02

                     DISTANCE TO LOAD-AXIS( 1)                                              THETA
                             0.                                                             0.
  DISPLACEMENTS
     RADIAL              TANGENTIAL              VERTICAL
    0.                    0.                     0.2854E-01
    STRESSES
     RADIAL              TANGENTIAL              VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
    0.8809E-01            0.8810E-01            -0.3874E 01            0.                  0.                  0.
    STRAINS
     RADIAL              TANGENTIAL              VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
    0.1926E-03            0.1926E-03            -0.4741E-03            0.                  0.                  0.
VERTICAL STRAIN =     -0.00047414          0.               0.              28.00
```

```
                                                  POSITION NUMBER  1

                                                   LAYER NUMBER   1

                                                    COORDINATES

                                           X              Y              Z
                                      0.             0.             0.7500E 01
                         DISTANCE TO LOAD-AXIS( 1)                                    THETA
                               0.                                                     0.
 DISPLACEMENTS
    RADIAL                TANGENTIAL            VERTICAL
  0.                       0.                   0.3355E-01
   STRESSES
    RADIAL                TANGENTIAL            VERTICAL            RAD./TANG.            RAD./VERT.           TANG./VERT.
  0.2952E 03               0.2952E 03          -0.3106E 02           0.                   0.                   0.
   STRAINS
    RADIAL                TANGENTIAL            VERTICAL            RAD./TANG.            RAD./VERT.           TANG./VERT.
  0.2633E-03               0.2633E-03          -0.3887E-03           0.                   0.                   0.
MAXIMUM NORMAL STRAIN =        0.00026330         0.           0.              7.50


                                                  POSITION NUMBER  2

                                                   LAYER NUMBER   3

                                                    COORDINATES

                                           X              Y              Z
                                      0.             0.             0.2800E 02
                         DISTANCE TO LOAD-AXIS( 1)                                    THETA
                               0.                                                     0.
 DISPLACEMENTS
    RADIAL                TANGENTIAL            VERTICAL
  0.                       0.                   0.2561E-01
   STRESSES
    RADIAL                TANGENTIAL            VERTICAL            RAD./TANG.            RAD./VERT.           TANG./VERT.
  0.9193E-01               0.9193E-01          -0.4043E 01           0.                   0.                   0.
   STRAINS
    RADIAL                TANGENTIAL            VERTICAL            RAD./TANG.            RAD./VERT.           TANG./VERT.
  0.2010E-03               0.2010E-03          -0.4948E-03           0.                   0.                   0.
VERTICAL STRAIN =      -0.00049475          0.           0.           28.00
```

```
                                                    POSITION NUMBER  1

                                                     LAYER NUMBER   1

                                                      COORDINATES

                                         X                Y              Z
                                    0.               0.              0.7500E 01
                 DISTANCE TO LOAD-AXIS( 1)                                            THETA
                       0.                                                             0.
DISPLACEMENTS
   RADIAL            TANGENTIAL            VERTICAL
 0.                    0.                  0.3495E-01
  STRESSES
   RADIAL            TANGENTIAL            VERTICAL            RAD./TANG.              RAD./VERT.            TANG./VERT.
 0.3075E 03            0.3075E 03         -0.3235E 02            0.                      0.                    0.
  STRAINS
   RADIAL            TANGENTIAL            VERTICAL            RAD./TANG.              RAD./VERT.            TANG./VERT.
 0.2743E-03            0.2743E-03         -0.3215E-03            0.                      0.                    0.
MAXIMUM NORMAL STRAIN =      0.00027427      0.                0.                  7.50


                                                    POSITION NUMBER  2

                                                     LAYER NUMBER   3

                                                      COORDINATES

                                         X                Y              Z
                                    0.               0.              0.2800E 02
                 DISTANCE TO LOAD-AXIS( 1)                                            THETA
                       0.                                                             0.
DISPLACEMENTS
   RADIAL            TANGENTIAL            VERTICAL
 0.                    0.                  0.2667E-01
  STRESSES
   RADIAL            TANGENTIAL            VERTICAL            RAD./TANG.              RAD./VERT.            TANG./VERT.
 0.9576E-01            0.9576E-01         -0.4211E 01            0.                      0.                    0.
  STRAINS
   RADIAL            TANGENTIAL            VERTICAL            RAD./TANG.              RAD./VERT.            TANG./VERT.
 0.2094E-03            0.2094E-03         -0.5154E-03            0.                      0.                    0.
VERTICAL STRAIN =   -0.00051537         0.                0.                  28.00
```

```
                                                   POSITION NUMBER  1

                                                    LAYER NUMBER   1

                                                     COORDINATES

                                            X             Y            Z
                                       0.            0.        0.7500E 01

                   DISTANCE TO LOAD-AXIS( 1)                                        THETA
                          0.                                                        0.
 DISPLACEMENTS
   RADIAL             TANGENTIAL           VERTICAL
  0.                    0.                 0.3635E-01
   STRESSES
   RADIAL             TANGENTIAL           VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.3198E 03            0.3198E 03         -0.3365E 02            0.                  0.                   0.
   STRAINS
   RADIAL             TANGENTIAL           VERTICAL            RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.2852E-03            0.2852E-03         -0.3344E-03            0.                  0.                   0.
MAXIMUM NORMAL STRAIN =        0.00028524        0.             0.            7.50


                   ALOAD =     20000.

                     PSI =     204.72

             FS =        8320.    XS =        0.        AS =      0.002168

 BS =     0.091745

 ................ABSC1 =    0.00028524      STRL2 =   0.00029464................



                   TOTAL ALLOWABLE WEIGHT =     54737.


 THICK ARRAY =
        7.50     20.50      0.        0.        0.        0.        0.        0.        0.

 KK =      1     THICK =     7.50

 KK =      2     THICK =    20.50

 SUBROUTINE POST.........
           1          0.            0.           0.           0.

           1          0.            0.           7.50         0.

           2          0.            0.           7.50         0.

           2          0.            0.          28.00         0.

           3          0.            0.          28.00         0.
```

```
                                    POSITION NUMBER  1

                                     LAYER NUMBER   1

                                      COORDINATES

                                 X            Y            Z
                            0.           0.           0.

                 DISTANCE TO LOAD-AXIS( 1)                                        THETA
                      0.                                                            0.
DISPLACEMENTS
   RADIAL               TANGENTIAL              VERTICAL
  0.                     0.                     0.3925E 01
   STRESSES
   RADIAL               TANGENTIAL              VERTICAL               RAD./TANG.            RAD./VERT.            TANG./VERT.
 -0.4403E 03            -0.4403E 03            -0.2047E 03               0.                    0.                    0.
   STRAINS
   RADIAL               TANGENTIAL              VERTICAL               RAD./TANG.            RAD./VERT.            TANG./VERT.
 -0.2786E-03            -0.2786E-03             0.1344E-03               0.                    0.                    0.

                           XX           YY           ZZ            YZ             XZ             XY            UX            UY            UZ
T O T A L   S T R E S S   -0.440E 03  -0.440E 03  -0.205E 03   0.            0.            0.
T O T A L   S T R A I N   -0.279E-03  -0.279E-03   0.134E-03   0.            0.            0.
T O T A L   D I S P L A C E M E N T                                                                     0.            0.          0.3725-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
              NORMAL         NORMAL          SHEAR          SHEAR              X               Y               Z
              STRESS         STRAIN          STRESS         STRAIN          COMPONENT       COMPONENT       COMPONENT
MAXIMUM     -0.205E 03     0.134E-03                                          0.              0.             1.000
MINIMAX     -0.440E 03    -0.279E-03                                          1.000           0.             0.
MINIMUM     -0.440E 03    -0.279E-03                                          0.              1.000          0.
MAXIMUM                                   0.118E 03     0.206E-03             0.             -0.707          0.707
            -0.323E 03                                                        0.              0.707          0.707
MINIMAX                                   0.118E 03     0.206E-03            -0.707           0.             0.707
            -0.323E 03                                                        0.707           0.             0.707
MINIMUM                                   0.172E-02     0.301E-08             0.707          -0.707          0.
            -0.440E 03                                                        0.707           0.707          0.

              STRAIN ENERGY 0.1089E 00
STRAIN ENERGY OF DISTORTION 0.3243E-01
```

```
                                        POSITION NUMBER  2

                                          LAYER NUMBER   1

                                            COORDINATES

                                   X             Y              Z
                              0.            0.            0.7500E 01

                  DISTANCE TO LOAD-AXIS( 1)                               THETA
                        0.                                                 0.
DISPLACEMENTS
   RADIAL             TANGENTIAL            VERTICAL
  0.                   0.                   0.3635E-01
  STRESSES
   RADIAL             TANGENTIAL            VERTICAL             RAD./TANG.         RAD./VERT.          TANG./VERT.
  0.3198E 03           0.3198E 03          -0.3365E 02            0.                 0.                   0.
  STRAINS
   RADIAL             TANGENTIAL            VERTICAL             RAD./TANG.         RAD./VERT.          TANG./VERT.
  0.2852E-03           0.2852E-03          -0.3344E-03            0.                 0.                   0.

                          XX          YY          ZZ          YZ          XZ          XY          UX          UY          UZ
T O T A L  S T R E S S    0.320E 03   0.320E 03  -0.336E 02   0.          0.          0.
T O T A L  S T R A I N    0.285E-03   0.285E-03  -0.334E-03   0.          0.          0.
T O T A L  D I S P L A C E M E N T                                                    0.          0.          0.3635E-01

P R I N C I P A L  V A L U E S  A N D  D I R E C T I O N S  O F  T O T A L  S T R E S S E S  A N D  S T R A I N S
            NORMAL        NORMAL          SHEAR          SHEAR              X              Y              Z
            STRESS        STRAIN          STRESS         STRAIN         COMPONENT      COMPONENT      COMPONENT
MAXIMUM    0.320E 03     0.285E-03                                        1.000          0.             0.
MINIMAX    0.320E 03     0.285E-03                                        0.             1.000          0.
MINIMUM   -0.336E 02    -0.334E-03                                        0.             0.             1.000
MAXIMUM                                 0.177E 03      0.310E-03          0.707          0.            -0.707
           0.143E 03                                                      0.707          0.             0.707
MINIMAX                                 0.177E 03      0.310E-03          0.             0.707         -0.707
           0.143E 03                                                      0.             0.707          0.707
MINIMUM                                 0.             0.                 0.707         -0.707          0.
           0.320E 03                                                      0.707          0.707          0.

            STRAIN ENERGY 0.9684E-01
STRAIN ENERGY OF DISTORTION 0.7308E-01
```

```
                                          POSITION NUMBER  3

                                           LAYER NUMBER   2

                                            COORDINATES

                                   X         Y          Z
                              0.        0.         0.7500E 01

                DISTANCE TO LOAD-AXIS( 1)                             THETA
                      0.                                              0.
DISPLACEMENTS
   RADIAL             TANGENTIAL          VERTICAL
  0.                    0.                0.3635E-01
  STRESSES
   RADIAL             TANGENTIAL          VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
 -0.4302E 00           -0.4302E 00        -0.3365E 02         0.                  0.                  0.
  STRAINS
   RADIAL             TANGENTIAL          VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
  0.2852E-03            0.2852E-03        -0.8273E-03         0.                  0.                  0.

                              XX          YY          ZZ          YZ          XZ          XY          UX          UY          UZ
T O T A L  S T R E S S    -0.430E 00  -0.430E 00  -0.336E 02   0.          0.          0.
T O T A L  S T R A I N     0.285E-03   0.285E-03  -0.827E-03   0.          0.          0.
T O T A L  D I S P L A C E M E N T                                                               0.          0.          0.3635E-01

P R I N C I P A L  V A L U E S  A N D  D I R E C T I O N S  O F  T O T A L  S T R E S S E S  A N D  S T R A I N S
              NORMAL        NORMAL          SHEAR          SHEAR              X               Y               Z
              STRESS        STRAIN          STRESS         STRAIN         COMPONENT       COMPONENT       COMPONENT
MAXIMUM    -0.430E 00     0.285E-03                                          0.             1.000           0.
MINIMAX    -0.430E 00     0.285E-03                                          1.000          0.              0.
MINIMUM    -0.336E 02    -0.827E-03                                          0.             0.              1.000
MAXIMUM                                   0.166E 02      0.556E-03           0.             0.707          -0.707
           -0.170E 02                                                        0.             0.707           0.707
MINIMAX                                   0.166E 02      0.556E-03           0.707          0.             -0.707
           -0.170E 02                                                        0.707          0.              0.707
MINIMUM                                   0.652E-07      0.182E-11          -0.707          0.707           0.
           -0.430E 00                                                        0.707          0.707           0.

                  STRAIN ENERGY 0.1388E-01
STRAIN ENERGY OF DISTORTION 0.1232E-01
```

```
                                                   POSITION NUMBER  4

                                                    LAYER NUMBER   2

                                                      COORDINATES

                                           X           Y           Z
                                       0.          0.          0.2800E 02

                  DISTANCE TO LOAD-AXIS( 1)                                   THETA
                        0.                                                    0.
DISPLACEMENTS
  RADIAL              TANGENTIAL               VERTICAL
 0.                    0.                      0.2774E-01
 STRESSES
  RADIAL              TANGENTIAL               VERTICAL              RAD./TANG.          RAD./VERT.           TANG./VERT.
 0.1114E 02            0.1114E 02              -0.4380E 01             0.                  0.                   0.
 STRAINS
  RADIAL              TANGENTIAL               VERTICAL              RAD./TANG.          RAD./VERT.           TANG./VERT.
 0.2177E-03            0.2177E-03              -0.3022E-03             0.                  0.                   0.

                               XX          YY          ZZ          YZ            XZ            XY            UX            UY            UZ
T O T A L  S T R E S S     0.111E 02   0.111E 02  -0.438E 01   0.            0.            0.
T O T A L  S T R A I N     0.218E-03   0.218E-03  -0.302E-03   0.            0.            0.
T O T A L  D I S P L A C E M E N T                                                                      0.            0.          0.277E-01

P R I N C I P A L  V A L U E S  A N D  D I R E C T I O N S  O F  T O T A L  S T R E S S E S  A N D  S T R A I N S
              NORMAL          NORMAL            SHEAR           SHEAR               X              Y              Z
              STRESS          STRAIN            STRESS          STRAIN          COMPONENT      COMPONENT      COMPONENT
MAXIMUM      0.111E 02       0.218E-03                                            1.000          0.             0.
MINIMAX      0.111E 02       0.218E-03                                            0.             1.000          0.
MINIMUM     -0.438E 01      -0.302E-03                                            0.             0.             1.000
MAXIMUM                                        0.776E 01       0.260E-03          0.707          0.            -0.707
             0.338E 01                                                            0.707          0.             0.707
MINIMAX                                        0.776E 01       0.260E-03          0.             0.707         -0.707
             0.338E 01                                                            0.             0.707          0.707
MINIMUM                                        0.              0.                 0.707         -0.707          0.
             0.111E 02                                                            0.707          0.707          0.

              STRAIN ENERGY 0.3088E-02
STRAIN ENERGY OF DISTORTION 0.2690E-02
```

```
                                                  POSITION NUMBER  5

                                                   LAYER NUMBER   3

                                                    COORDINATES

                                             X             Y              Z
                                         0.            0.          0.2000E 02

                    DISTANCE TO LOAD-AXIS( 1)                                        THETA
                          0.                                                          0.
DISPLACEMENTS
   RADIAL               TANGENTIAL              VERTICAL
  0.                      0.                    0.2974E-01
   STRESSES
   RADIAL               TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.            TANG./VERT.
  0.9959E-01              0.9959E-01            -0.4380E 01          0.                 0.                    0.
   STRAINS
   RADIAL               TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.            TANG./VERT.
  0.2177E-03              0.2177E-03            -0.5360E-03          0.                 0.                    0.

                                XX            YY          ZZ           YZ           XZ          XY          UX          UY          UZ
T O T A L   S T R E S S     0.996E-01    0.996E-01   -0.438E 01    0.           0.          0.
T O T A L   S T R A I N     0.218E-03    0.218E-03   -0.536E-03    0.           0.          0.
T O T A L   D I S P L A C E M E N T                                                                  0.          0.      0.377E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
                 NORMAL            NORMAL               SHEAR             SHEAR               X                  Y                 Z
                 STRESS            STRAIN               STRESS            STRAIN          COMPONENT          COMPONENT         COMPONENT
MAXIMUM        0.996E-01         0.218E-03                                                    0.              1.000              0.
MINIMAX        0.996E-01         0.218E-03                                                    1.000           0.                 0.
MINIMUM       -0.438E 01        -0.536E-03                                                    0.              0.                 1.000
MAXIMUM                                              0.224E 01         0.377E-03              0.              0.707             -0.707
              -0.214E 01                                                                      0.              0.707              0.707
MINIMAX                                              0.224E 01         0.377E-03              0.707           0.                -0.707
              -0.214E 01                                                                      0.707           0.                 0.707
MINIMUM                                              0.307E-07         0.546E-11             -0.707           0.707              0.
               0.996E-01                                                                      0.707           0.707              0.

               STRAIN ENERGY 0.1198E-02
STRAIN ENERGY OF DISTORTION 0.1120E-02
```

INPUT GUIDE FOR RIGID PAVEMENTS

Line 1

Title 80 Characters

Line 2

NYSYS

NSYS = number of problems to run

Line 3

EKEY	EKEY2

EKEY = Limiting strain and stress subroutine code: set - 3, for calls to subroutine RPAL

EKEY2 = Pavement problem code: set = 0, for allowable load

Line 4

DSM	FAC	YRN	R	ALOAD	ALIN	CAREA	SWL

DSM = Dynamic stiffnes modulus, for reference

FAC = Pass-to-coverage ratio

YRN = Yearly load repetition number

R = Flexural strength, psi

ALOAD = Initial load, lb

ALIN = Load increment, lb

CAREA = Contact area (πr^2), in.^{2}

SWL = : set = 0

Line 5

NLAYS	ISMO	IRED

NLAYS = Number of layers in pavement system

ISMO = Request for smooth computational procedure: set = 1

IRED = Input format for Line 6: set = 1

Line 6-1 through 6-(NLAYS-1) (one for each layer, except last layer)

E(i)	NU(i)	THICK(i)	ALK(i)

E(i) = Modulus of layer i

NU(i) = Poisson's ratio of layer i

THICK(i) = Thickness of layer i

ALK(i) = Reduced interface compliance: set; ALK(1) = 1000, all other ALK(i)'s = 0

Line 7

E(NLAYS)	NU(NLAYS)

E(NLAYS) = Modulus of last layer

NU(NLAYS) = Poisson's ratio of last layer

Line 8

NLOAD

NLOAD = Number of loaded areas

Line 9 (one for each load)

LOSTRS(i)	RADIUS(i)	X(i)	Y(i)	HOSTR(i)	PSI(i)

LOSTRS(i) = Vertical load for load area i

RADIUS(i) = Radius of loaded area i

X(i) = Abscissa of center of loaded area: set = 0

HOSTR(i) = Horizontal load for load area i: normally = 0

PSI(i) = Angle of Hostr(i) with respect to positive x-axis in degrees: normally = 0

Line 10

NPOS

NPOS = Number of depths that will be used for iteration purposes: set = 1

Line 11-1 through 11-NPOS

LAYER(i)	AX(i)	AY(i)	DEPTH(i)	ETA(i)

LAYER(i) = Layer number for position i; set = 1

AX(1) = Abscissa of position: set = 0

AY(1) = Ordinate of position: set = 0

DEPTH(1) = Depth from pavement surface to position; set = THICK(1)

ETA(1) = Angle from which position is observed: set = 0

TYPICAL INPUT FOR RIGID PAVEMENT EVALUATION

```
010##N
020$:IDENT:ROSF300,BUSH
030$:OPTION:FORTRAN
040$:MSG3:060480/1700
050$:USE:.GTLIT
060$:FORTY:XFEF
070$:SELECTA:PAVEVAL
080$:NOTE:PAVEVAL
090$:EXECUTE
100$:LIMITS:30,30K,,15000
110PCC ROAD  SECTION 8                          LINE 1
120  1                                           LINE 2
130  3 0                                         LINE 3
140  1000 7.94 25000 799 15000 1000 127 0        LINE 4
150  3 1 1                                       LINE 5
160  4000000 0.15  6 1000                        LINE 6-1
170  78787   0.30 10 0                           LINE 6-2
180  12278   0.40                                LINE 7
190  1                                           LINE 8
200  9500 6.36 0 0 0 0                           LINE 9
210  1                                           LINE 10
220  1 0 0  6 0                                  LINE 11-1
230$:ENDJOB

READY
```

TYPICAL OUTPUT FOR RIGID PAVEMENT EVALUATION

```
                    TCC ROAD  SECTION 5

**************************************************
                 A    =   0.585810

                 K    =   0.354860

                 YRM  =     25000.

                 FAC  =     7.9400

                 FCV  =     52972.
**************************************************

* * * * *   R I G I D   P A V E M E N T   A L L O W A B L E   L O A D * * * * *


**************************************************
                 FS     =   799.

                 DSM    =  1000.

                 NLOAD  = 15000.

                 NLIM   =  1000.

                 TTTL   =    348.5953?145
**************************************************
```

```
                                              POSITION NUMBER  1
                                               LAYER NUMBER  1
                                                COORDINATES
                                    X           Y           Z
                             0.          0.          0.8000E 01

                DISTANCE TO LOAD-AXIS( 1)                            THETA
                    0.                                               0.
 DISPLACEMENTS
     RADIAL             TANGENTIAL              VERTICAL
   0.                     0.                    0.1537E-01
    STRESSES
     RADIAL             TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
   0.3533E 03            0.3630E 03            -0.1170E 02           0.                  0.                  0.
    STRAINS
     RADIAL             TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
   0.7758E-04            0.7758E-04            -0.3815E-04           0.                  0.                  0.
 MAXIMUM NORMAL STRESS =    362.99581528        0.           0.           6.00


                                              SYSTEM NUMBER    1


 LAYER    CALCULATION  YOUNG'S     POISSON'S    THICKNESS    REDUCED
 NUMBER   METHOD       MODULUS     RATIO                     SPRINGCOMPL
    1     SMOOTH     0.4000E 07  0.1500E 00  0.8000E 01  0.1000E 04
    2     SMOOTH     0.7877E 05  0.3000E 00  0.3000E 02  0.
    3                0.1228E 05  0.4000E 00


 LOAD     NORMAL           SHEAR       RADIUS OF        LOAD - POSITION         SHEAR
 NUMBER   STRESS           STRESS      LOADED AREA       X            Y         DIRECTION
    1    0.1180E 03  0.                0.6360E 01  0.            0.            0.
```

```
****************************************************************
****************************************************************
                    ALOAD =     15000.
                    PSI   =        0.
                    FS    =   299.
                    DSM   =  1000.
                    RSTS  =    362.99581928
                    STSL  =    340.59838145
****************************************************************
****************************************************************



                    TOTAL ALLOWABLE WEIGHT =     31579.


THICK ARRAY =
      6.00     10.00      0.        0.        0.        0.        0.        0.        0.
KK =     1     THICK =     6.00
KK =     2     THICK =    10.00
SUBROUTINE POST---------
         1          0.             0.            0.           0.
         1          0.             0.            6.00         0.
         2          0.             0.            6.00         0.
         2          0.             0.           16.00         0.
         3          0.             0.           16.00         0.
```

```
                                                    POSITION NUMBER  1

                                                    LAYER NUMBER   1

                                                    COORDINATES

                                               X          Y          Z
                                          0.         0.         0.

                       DISTANCE TO LOAD-AXIS( 1)                                     THETA
                           0.                                                        0.
DISPLACEMENTS
    RADIAL              TANGENTIAL              VERTICAL
  0.                      0.                    0.1847E-01
   STRESSES
    RADIAL              TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
 -0.3949E 03             -0.3949E 03            -0.1180E 03          0.                  0.                  0.
   STRAINS
    RADIAL              TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
 -0.7949E-04             -0.7949E-04            0.1078E-06           0.                  0.                  0.

                               XX          YY          ZZ          YZ          XZ          XY          UX          UY          UZ
T O T A L  S T R E S S     -0.395E 03  -0.395E 03  -0.118E 03   0.          0.          0.
T O T A L  S T R A I N     -0.795E-04  -0.795E-04   0.107E-06   0.          0.          0.
T O T A L  D I S P L A C E M E N T                                                                  0.          0.          0.155E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
                NORMAL          NORMAL          SHEAR           SHEAR               X               Y               Z
                STRESS          STRAIN          STRESS          STRAIN          COMPONENT       COMPONENT       COMPONENT
MAXIMUM      -0.118E 03       0.107E-06                                            0.              0.              1.000
MINIMAX      -0.395E 03      -0.795E-04                                            0.              1.000           0.
MINIMUM      -0.395E 03      -0.795E-04                                            1.000           0.              0.
MAXIMUM                                      0.138E 03       0.398E-04            -0.707           0.              0.707
             -0.256E 03                                                            0.707           0.              0.707
MINIMAX                                      0.138E 03       0.398E-04             0.             -0.707           0.707
             -0.256E 03                                                            0.              0.707           0.707
MINIMUM                                      0.954E-05       0.273E-11            -0.707           0.707           0.
             -0.395E 03                                                            0.707           0.707           0.

                 STRAIN ENERGY 0.3138E-01
STRAIN ENERGY OF DISTORTION 0.7346E-02
```

```
                                                    POSITION NUMBER  2

                                                     LAYER NUMBER   1

                                                      COORDINATES

                                                 X            Y             Z
                                            0.           0.          0.800CE 01

                              DISTANCE TO LOAD-AXIS( 1)                                THETA
                                  C.                                                    0.
DISPLACEMENTS
   RADIAL               TANGENTIAL            VERTICAL
 0.                      0.                   0.1837E 01
  STRESSES
   RADIAL               TANGENTIAL            VERTICAL               RAD./TANG.           RAD./VERT.            TANG./VERT.
 0.3630E 03              0.3630E 03           -0.1170E 02              0.                   0.                    0.
  STRAINS
   RADIAL               TANGENTIAL            VERTICAL               RAD./TANG.           RAD./VERT.            TANG./VERT.
 0.7758E-04              0.7758E-04           -0.3015E-04              0.                   0.                    0.

                                 XX           YY          ZZ            YZ           XZ            XY            UX         UY           UZ
T O T A L  S T R E S S       0.363E 03    0.363E 03   -0.117E 02     0.           0.            0.
T O T A L  S T R A I N       0.776E-04    0.776E-04   -0.301E-04     0.           0.            0.
T O T A L  D I S P L A C E M E N T                                                                            0.         0.         0.154E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
                 NORMAL            NORMAL           SHEAR             SHEAR              X                  Y                  Z
                 STRESS            STRAIN           STRESS            STRAIN         COMPONENT          COMPONENT          COMPONENT
MAXIMUM        0.363E 03        0.776E-04                                              1.000               0.                 0.
MINIMAX        0.363E 03        0.776E-04                                              0.                  1.000              0.
MINIMUM       -0.117E 02       -0.301E-04                                              0.                  0.                 1.000
MAXIMUM                                         0.187E 03         0.539E-04            0.707               0.                -0.707
               0.176E 03                                                               0.707               0.                 0.707
MINIMAX                                         0.187E 03         0.539E-04            0.                  0.707             -0.707
               0.176E 03                                                               0.                  0.707              0.707
MINIMUM                                         0.191E-04         0.546E-11            0.707              -0.707              0.
               0.363E 03                                                               0.707               0.707              0.

                 STRAIN ENERGY 0.2034E-01
STRAIN ENERGY OF DISTORTION 0.1345E-01
```

```
                                                  POSITION NUMBER  3

                                                   LAYER NUMBER   2

                                                   COORDINATES

                                               X            Y            Z
                                          0.           0.           0.6000E 01

                   DISTANCE TO LOAD-AXIS( 1)                                        THETA
                       0.                                                           0.
DISPLACEMENTS
   RADIAL               TANGENTIAL             VERTICAL
 0.                      0.                    0.1537E-01
  STRESSES
   RADIAL               TANGENTIAL             VERTICAL           RAD./TANG.         RAD./VERT.          TANG./VERT.
 -0.6676E 01             -0.6676E 01           -0.1170E 02          0.                 0.                  0.
  STRAINS
   RADIAL               TANGENTIAL             VERTICAL           RAD./TANG.         RAD./VERT.          TANG./VERT.
 -0.1479E-04             -0.1477E-04           -0.9765E-04          0.                 0.                  0.

                              XX           YY           ZZ          YZ           XZ           XY          DX          DY          DZ
T O T A L   S T R E S S   -0.666E 01  -0.668E 01  -0.117E 02   0.           0.           0.
T O T A L   S T R A I N   -0.148E-04  -0.148E-04  -0.976E-04   0.           0.           0.
T O T A L   D I S P L A C E M E N T                                                               0.          0.          0.154E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
               NORMAL          NORMAL           SHEAR            SHEAR                X                Y                Z
               STRESS          STRAIN           STRESS           STRAIN           COMPONENT        COMPONENT        COMPONENT
MAXIMUM      -1.668E 01     -0.148E-04                                               0.               1.000            0.
MINIMAX      -1.668E 01     -0.148E-04                                               1.000            0.               0.
MINIMUM      -0.117E 02     -0.976E-04                                               0.               0.               1.000
MAXIMUM                                       0.251E 01        0.414E-04             0.               0.707           -0.707
             -1.919E 01                                                              0.               0.707            0.707
MINIMAX                                       0.251E 01        0.414E-04             0.707            0.              -0.707
             -1.919E 01                                                              0.707            0.               0.707
MINIMUM                                       0.192E-03        0.318E-08            -0.707            0.707            0.
             -1.668E 01                                                              0.707            0.707            0.

             STRAIN ENERGY 0.6696E 03
STRAIN ENERGY OF DISTORTION 0.1387E-42
```

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                                   POSITION NUMBER  4
                                     LAYER NUMBER    2
                                       COORDINATES
                                 X              Y              Z
                           0.             0.            0.1600E 02
                   DISTANCE TO LOAD-AXIS( 1)                            THETA
                         0.                                             0.
DISPLACEMENTS
  RADIAL               TANGENTIAL           VERTICAL
 0.                     0.                  0.1827E-01
  STRESSES
  RADIAL               TANGENTIAL           VERTICAL           RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.9995E 01             0.9995E 01         -0.4136E 01          0.                  0.                  0.
  STRAINS
  RADIAL               TANGENTIAL           VERTICAL           RAD./TANG.          RAD./VERT.          TANG./VERT.
 0.1046E-03             0.1046E-03         -0.1286E-03          0.                  0.                  0.

                            XX          YY          ZZ          YZ          XZ          XY          UX          UY          UZ
T O T A L   S T R E S S    0.100E 02   0.100E 02  -0.414E 01   0.          0.          0.
T O T A L   S T R A I N    0.105E-03   0.105E-03  -0.129E-03   0.          0.          0.
T O T A L   D I S P L A C E M E N T                                                             0.          0.          0.143E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
              NORMAL         NORMAL            SHEAR           SHEAR             X              Y              Z
              STRESS         STRAIN            STRESS          STRAIN         COMPONENT      COMPONENT      COMPONENT
MAXIMUM      0.100E 02      0.105E-03                                          1.000          0.             0.
MINIMAX      0.100E 02      0.105E-03                                          0.             1.000          0.
MINIMUM     -0.414E 01     -0.129E-03                                          0.             0.             1.000
MAXIMUM                                      0.707E 01       0.117E-03         0.707          0.            -0.707
             0.293E 01                                                         0.707          0.             0.707
MINIMAX                                      0.707E 01       0.117E-03         0.             0.707         -0.707
             0.293E 01                                                         0.             0.707          0.707
MINIMUM                                      0.596E-07       0.909E-12         0.707         -0.707          0.
             0.100E 02                                                         0.707          0.707          0.

                   STRAIN ENERGY 0.1311E-02
STRAIN ENERGY OF DISTORTION 0.1099E-02
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                                                  POSITION NUMBER  5

                                                   LAYER NUMBER    3

                                                     COORDINATES
                                           X              Y              Z
                                        0.             0.             0.1600E 02

                 DISTANCE TO LOAD-AXIS( 1)                                 THETA
                       0.                                                  0.
DISPLACEMENTS
   RADIAL            TANGENTIAL              VERTICAL
 0.                   0.                      0.1427E-02
  STRESSES
   RADIAL            TANGENTIAL              VERTICAL              RAD./TANG.          RAD./VERT.           TANG./VERT.
 -0.6178E 00         -0.6178E 00             -0.4136E 01            0.                  0.                   0.
  STRAINS
   RADIAL            TANGENTIAL              VERTICAL              RAD./TANG.          RAD./VERT.           TANG./VERT.
  0.1046E-03          0.1046E-03             -0.2968E-03            0.                  0.                   0.

                             XX           YY           ZZ           XZ            YZ           XY           QX           QY           QZ
T O T A L   S T R E S S   -0.618E 00   -0.618E 00   -0.414E 01    0.            0.           0.
T O T A L   S T R A I N    0.105E-03    0.105E-03   -0.297E-03    0.            0.           0.
T O T A L   D I S P L A C E M E N T                                                                       0.           0.           0.143E-01

P R I N C I P A L   V A L U E S   A N D   D I R E C T I O N S   O F   T O T A L   S T R E S S E S   A N D   S T R A I N S
               NORMAL          NORMAL         SHEAR           SHEAR              X                  Y                  Z
               STRESS          STRAIN         STRESS          STRAIN         COMPONENT          COMPONENT          COMPONENT
MAXIMUM     -0.618E 00      0.105E-03                                          0.                 1.000              0.
MINIMAX     -0.618E 00      0.105E-03                                          1.000              0.                 0.
MINIMUM     -0.414E 01     -0.297E-03                                          0.                 0.                 1.000
MAXIMUM                                    0.176E 01       0.281E-03           0.                 0.707             -0.707
            -0.238E 01                                                         0.                 0.707              0.707
MINIMAX                                    0.176E 01       0.281E-03           0.707              0.                -0.707
            -0.238E 01                                                         0.707              0.                 0.707
MINIMUM                                    0.291E-07       0.318E-11          -0.707              0.707              0.
            -0.618E 00                                                         0.707              0.707              0.

                STRAIN ENERGY 0.5400E-03
STRAIN ENERGY OF DISTORTION 0.4284E-03
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DAT

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