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16. Abstract

Presented in this report is a theoretical study of the effects of varying the modulus and thickness of asphalt concrete surfacing materials. Three typical flexible pavement design problems at two levels of hot mix asphaltic concrete (HMAC) elastic modulus are analyzed using linear elastic theory. Specific findings are: (1) the use of an HMAS modulus which is much higher than the base course modulus, is discouraged, (2) if a high HMAC - base course modular ratio cannot be avoided, then one should avoid the range from 1 inch to 6 inches of HMAC thickness, and (3) the softening of the base material immediately under the surface layer results in higher tensile stresses at the bottom of the surface layer, and accelerates fatigue deterioration of the pavement.

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THE EFFECT OF VARYING THE MODULUS AND THICKNESS OF ASPHALTIC CONCRETE SURFACING MATERIALS

by

Danny Y. Lu
Frank H. Scrivner

Research Report Number 123-24

A System Analysis of Pavement Design
and Research Implementation

Research Project 1-8-69-123

conducted for

The Texas Highway Department

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

Highway Design Division
Texas Highway Department

Texas Transportation Institute
Texas A&M University

Center for Highway Research
The University of Texas at Austin

October, 1974

DISCLAIMER

PREFACE

This report is one of a series issued under Research Study 1-8-69-123, "A System Analysis of Pavement Design and Research Implementation". Study 123 is being conducted jointly by principal investigators and their staffs in three agencies -- The Texas Highway Department at Austin, The Center for Highway Research at Austin, and The Texas Transportation Institute at College Station, as a part of the cooperative research program with the Department of Transportation, Federal Highway Administration.

ACKNOWLEDGMENT

The authors are very grateful to Mr. James L. Brown of the Texas Highway Department and Dr. Robert L. Lytton of Texas Transportation Institute for their helpful discussions.

LIST OF REPORTS

Report No. 123-1, "A Systems Approach Applied to Pavement Design and Research," by W. Ronald Hudson, B. Frank McCullough, F.H. Scrivner, and James L. Brown, describes a long-range comprehensive research program to develop a pavement systems analysis and presents a working systems model for the design of flexible pavements, March 1970.

Report No. 123-2, "A Recommended Texas Highway Department Pavement Design System Users Manual," by James L. Brown, Larry J. Buttler, and Hugo E. Orellana, is a manual of instructions to Texas Highway Department personnel for obtaining and processing data for flexible pavement design system, March 1970.

Report No. 123-3, "Characterization of the Swelling Clay Parameter Used in the Pavement Design System," by Arthur W. Witt, III, and B. Frank McCullough, describes the results of a study of the swelling clays parameter used in pavement design system, August 1970.

Report No. 123-4, "Developing A Pavement Feedback Data System," by R.C.G. Haas, describes the initial planning and development of a pavement feedback data system, February 1971.

Report No. 123-5, "A Systems Analysis of Rigid Pavement Design," by Ramesh K. Kher, W.R. Hudson, and B.F. McCullough, describes the development of a working systems model for the design of rigid pavements, November 1970.

Report No. 123-6, "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections," by F.H. Scrivner, C.H. Michalak, and William M. Moore, describes a computer program which will serve as a subsystem of a future Flexible Pavement System founded on linear elastic theory, March 1971.

Report No. 123-6A, "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections, Part II," by Frank H. Scrivner, Chester H. Michalak, and William M. Moore, is a supplement to Report No. 123-6 and describes the effect of a change in the specified location of one of the deflection points, December 1971.

Report No. 123-7, "Annual Report on Important 1970-71 Pavement Research Needs," by B. Frank McCullough, James L. Brown, W. Ronald Hudson, and F.H. Scrivner, describes a list of priority research items based on findings from use of the pavement design system, April 1971.

Report No. 123-8, "A Sensitivity Analysis of Flexible Pavement System FPS2," by Ramesh K. Kher, B. Frank McCullough, and W. Ronald Hudson, describes the overall importance of this system, the relative importance of the variables of the system and recommendations for efficient use of the computer program, August 1971.

Report No. 123-9, "Skid Resistance Considerations in the Flexible Pavement Design System," by David C. Steitle and B. Frank McCullough describes skid resistance consideration in the Flexible Pavement System based on the testing of aggregates in the laboratory to predict field performance and presents a nomograph for the field engineer to use to eliminate aggregates which would not provide adequate skid resistance performance, April 1972.

Report No. 123-10, "Flexible Pavement System - Second Generation, Incorporating Fatigue and Stochastic Concepts," by Surendra Prakash Jain, B. Frank McCullough and W. Ronald Hudson, describes the development of new structural design models for the design of flexible pavement which will replace the empirical relationship used at present in flexible pavement systems to simulate the transformation between the input variables and performance of a pavement, January 1972.

Report No. 123-11, "Flexible Pavement System Computer Program Documentation," by Dale L. Schafer, provides documentation and an easily updated documentation system for the computer program FPD-9, April 1972.

Report No. 123-13, "Benefit Analysis for Pavement Design System," by Frank McFarland, presents a method for relating motorist's costs to the pavement serviceability index and a discussion of several different methods of economic analysis.

Report No. 123-14, "Prediction of Low-Temperature and Thermal-Fatigue Cracking in Flexible Pavements," by Mohamed Y. Shahin and B. Frank McCullough, describes a design system for predicting temperature cracking in asphalt concrete surfaces, August 1972.

Report No. 123-15, "FPS-11 Flexible Pavement System Computer Program Documentation," by Hugo E. Orellana, gives the documentation of the computer program FPS-11, October 1972.

Report No. 123-16, "Fatigue and Stress Analysis Concepts for Modifying the Rigid Pavement Design System," by Piti Yimprasett and B. Frank McCullough, describes the fatigue of concrete and stress analyses of rigid pavement, October 1972.

Report No. 123-17, "The Optimization of a Flexible Pavement System Using Linear Elasticity," by Danny Y. Lu, Chia Shun Shih, and Frank H. Scrivner describes the integration of the current Flexible Pavement System computer program and Shell Oil Company's program BISTRO, for elastic layered systems, with special emphasis on economy of computation and evaluation of structural feasibility of materials, March 1973.

Report No. 123-18, "Probabilistic Design Concepts Applied to Flexible Pavement System Design," by Michael I. Darter and W. Ronald Hudson, describes the development and implementation of the probabilistic design approach and its incorporation into the Texas flexible pavement design system for new construction and asphalt concrete overlay, May 1973.

Report No. 123-19, "The Use of Condition Surveys, Profile Studies, and Maintenance Studies in Relating Pavement Distress ot Pavement Performance," by Robert P. Smith and B. Frank McCullough, introduces the area of relating pavement distress to pavement performance, presents work accomplished in this area, and gives recommendations for future research, August 1973.

Report No. 123-20, "Implementation of a Complex Research Development of Flexible Pavement Design System into Texas Highway Department Design Operations," by Larry Buttler and Hugo Orellana, describes the step-by-step process used in incorporating the implementation research into the actual working operation.

Report No. 123-21, "Rigid Pavement Design System, Input Guide for Program RPS2 In Use by the Texas Highway Department," by R. Frank Carmichael and B. Frank McCullough, describes the input variables necessary to use the Texas rigid pavement design system program RPS2, January 1974 (subject to approval)

Report No. 123-22, "An Integrated Pavement Design Processor," by Danny Y. Lu," Chia Shun Shih, Frank H. Scrivner, and Robert L. Lytton, provides a comprehensive decision framework with a capacity to drive different pavement design programs at the user's command through interactive queries between the computer and the design engineers.

Report No. 123-23, "Stochastic Study of Design Parameters and Lack-of-Fit of Performance Model in the Texas Flexible Pavement Design System," by Malvin Holsen and W. Ronald Hudson, describes a study of initial serviceability index of flexible pavements and a method for quantifying lack-of-fit of the performance equation.

Report No. 123-24, "The Effect of Varying the Modulus and Thickness of Asphaltic Concrete Surfacing Materials," by Danny Y. Lu and Frank H. Scrivner, investigates the effect on the principal stresses and strains in asphaltic concrete resulting from varying the thickness and modulus of that material when used as the surfacing of a typical flexible pavement.

Report No. 123-25, "Linear Elastic Layer Theory as a Model of Displacements Measured Within and Beneath Flexible Pavement Structures Loaded by the Dynaflect," by Frank H. Scrivner and Chester H. Michalak, compares predictions from linear elasticity with measured values of vertical and horizontal displacements at the surface of flexible pavements, within the pavement structures, within the embankments, and within the foundation material.

ABSTRACT

Presented in this report is a theoretical study of the effects of varying the modulus and thickness of asphalt concrete surfacing materials. Three typical flexible pavement design problems at two levels of hot mix asphaltic concrete (HMAC) elastic modulus are analyzed using linear elastic theory. Specific findings are: (1) the use of an HMAC modulus which is much higher than the base course modulus, is discouraged, (2) if a high HMAC - base course modular ratio cannot be avoided, then one should avoid the range from 1 inch to 6 inches of HMAC thickness, and (3) the softening of the base material immediately under the surface layer results in higher tensile stresses at the bottom of the surface layer, and accelerates fatigue deterioration of the pavement.

KEY WORDS: Linear Elasticity, Flexible Pavement Design.

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INTRODUCTION

The purpose of this study is to investigate the effect of varying the modulus and thickness of asphaltic concrete surfacing materials. Principal stresses and strains, as well as vertical deflections of flexible pavement structures, under a standardized dual-wheel load, are analyzed based on linear elastic theory. Three typical flexible pavement design problems are selected to illustrate the effects. Each problem is divided into two series: the elastic modulus of the surface layer is assigned a value of 500,000 psi in series 1 and 100,000 psi in series 2.

The three design problems are briefed below.

Problem 1 investigates the variations of major principal stresses and strains as well as vertical deflections of a three-layer design at a surface point between the dual-wheel loads and a point at the bottom of the top layer under one of the loads, versus the thickness of the top layer. Problem 2 investigates the variations of major principal stresses and strains as well as vertical deflections of a three-layer design at the top and bottom of the top layer in a vertical plane through the truck axle. The top layer is assumed to be very thin (0.5 inches). Problem 3 investigates the variations of major principal stresses and strains as well as vertical deflections at layer interfacial points of a four-layer design, versus the elastic modulus of the second layer. The second layer is assumed to be very thin (0.5 inches), and simulates that portion of a base material likely to become saturated under certain climatic conditions sometimes occurring in west Texas. The surface layer is three inches thick, typical of many west Texas pavements.

It is anticipated that results of this study can be used to introduce certain restraints in the Texas Flexible Pavement Design System (1) to avoid thickness-stiffness combinations in hot mixed asphaltic concrete (HMAC) that lead to surface cracking.

PROBLEM 1: CRITICAL HMAC THICKNESS

Problem 1 investigates two series of flexible pavement structures. Series 1 simulates existing west Texas surfacing, base and subgrade materials to show critical HMAC thickness. Using the same base and subgrade material characteristics, series 2 is analyzed to see how lower modulus HMAC material would change the critical surfacing thickness. It must be noted that the present surface treatment pavements in Texas are believed to be characterized in series 2, but not the present HMAC pavements.

The sketch in Figure 1 represents a pavement cross section composed of three layers. The top layer is the HMAC surface and the bottom layer is the subgrade. Materials for each layer are characterized by the elastic modulus, E_i, and Poisson's ratio, ν_i, where the subscript, i, designates the position of the layer in the structure. Layers are numbered consecutively from the top layer downward. Table 1 shows the characteristics assigned to the materials treated in Problem 1. The ratio of E_1/E_2 is 10 in series 1, and 2 in series 2. The thickness of the i^{th} layer is represented by D_i. The top layer thickness, D_1, varies at four levels: 0.33, 1, 3 and 9 inches. D_2 has two levels: 4 and 12 inches. The subgrade thickness, D_3, is considered to be infinite.

An 18 kip single axle load is assumed to be applied to the pavement surface through four tires. Figure 1 shows the dual-

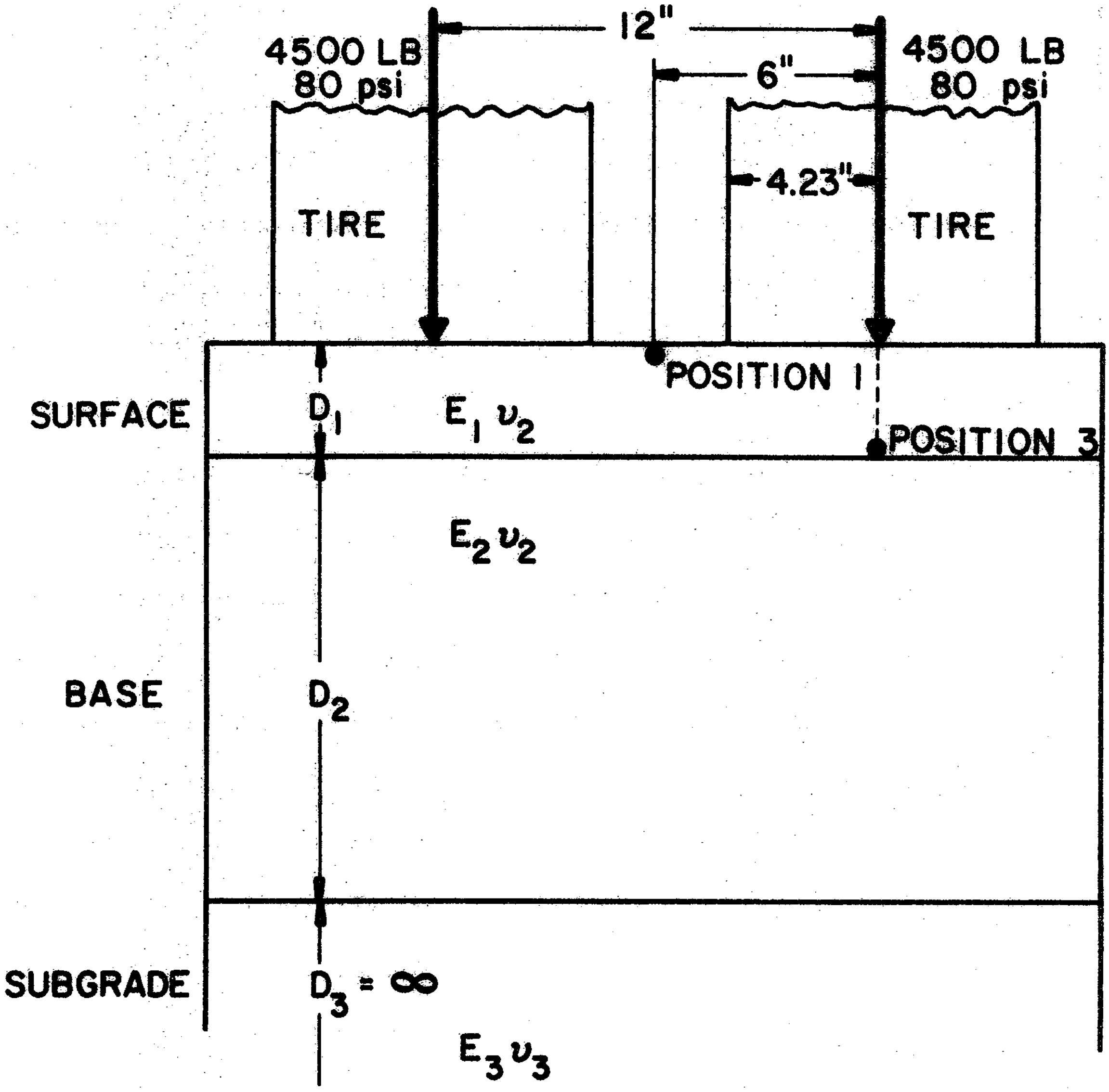

FIG. 1 PAVEMENT STRUCTURE AND DUAL-WHEEL LOADS OF PROBLEM 1

TABLE 1

MATERIAL CHARACTERISTICS OF PROBLEM 1

	Surface	Base	Subgrade
Elastic Modulus (psi)	E_1*	50,000	20,000
Poisson's Ratio	0.5	0.5	0.5

*E_1 = 500,000 (series 1)
= 100,000 (series 2)

wheel load at one end of the design axle. Two 4,500 lb. loads are assumed to be distributed at a uniform pressure of 80 psi over two circular areas, 12 inches center-to-center.

Two positions within the layered pavement structure are studied. As indicated in Figure 1, position 1 is a surface point between the dual-wheel loads; and position 3 is at the bottom of the top layer under one of the dual-wheel loads.

It is of interest to know, judged by the major principal stress: (1) when is position 1 critical? (2) when is position 3 critical? and (3) what is the effect of lowering the ratio E_1/E_2 from 10 to 2?

A streamlined BISTRO computer program (2) is utilized to solve this problem. The major principal stress, σ_I, and strain, ε_I, as well as the vertical deflection, w, versus surface layer thickness at the two designated positions, are summarized in Tables 2 and 3, at two levels of D_2 and two levels of E_1/E_2 ratio. The vertical deflection at position 3 is not included in this study.

TABLE 2

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 1 WHEN $E_1/E_2 = 10$

Position	D_1 (in.)	D_2					
		4 in.			20 in.		
		σ_I (psi)	ε_I	w(in.)	σ_I (psi)	ε_I	w(in.)
1	0.33	0.375E 01	0.991E-04	.0192	0.394E 02	0.857E-04	.0117
	1.00	0.677E 02	0.227E-03	.0191	0.109E 03	0.233E-03	.0120
	3.00	0.0	0.263E-03	.0159	0.0	0.158E-03	.0113
	9.00	0.0	0.119E-03	.0082	0.0	0.966E-04	.0069
3	0.33	-0.790E 02	0.135E-04	-----	-0.360E 02	0.467E-04	-----
	1.00	0.147E 03	0.233E-03	-----	0.121E 03	0.209E-03	-----
	3.00	0.207E 03	0.269E-03	-----	0.166E 03	0.227E-03	-----
	9.00	0.755E 02	0.921E-04	-----	0.627E 02	0.810E-04	-----

TABLE 3

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 1 WHEN $E_1/E_2 = 2$

Position	D_1 (in.)	D_2					
		4 in.			20 in.		
		σ_I (psi)	ε_I	w(in.)	σ_I (psi)	ε_I	w(in.)
1	0.33	0.0	0.261E-03	.0194	0.0	0.435E-04	.0117
	1.00	0.0	0.155E-03	.0189	0.144E 02	0.152E-03	.0117
	3.00	0.0	0.302E-03	.0172	0.0	0.976E-04	.0116
	9.00	0.0	0.201E-03	.0119	0.0	0.121E-03	.0093
3	0.33	-0.795E 02	0.195E-03	-----	-0.689E 02	0.583E-04	-----
	1.00	-0.467E 02	0.159E-03	-----	-0.368E 02	0.227E-03	-----
	3.00	0.247E 02	0.426E-03	-----	0.175E 02	0.410E-03	-----
	9.00	0.220E 02	0.213E-03	-----	0.145E 02	0.190E-03	-----

Figure 2 presents plots of the major principal stress versus surface layer thickness to show the critical HMAC thickness. Specific findings are as follows:

1. When $E_1/E_2 = 10$ and $D_2 = 4$ in.,
   a. If $D_1 < 0.33$ in., then there is no tension or negligible tension at either point;
   b. If 0.33 in. $< D_1 < 0.5$ in., then point 1 is critical;
   c. If $D_1 > 0.5$ in., then point 3 is critical.

2. When $E_1/E_2 = 10$ and $D_2 = 20$ in.,
   a. If $D_1 < 0.8$ in., then point 1 is critical;
   b. If $D_1 > 0.8$ in., then point 3 is critical.

3. When $E_1/E_2 = 2$ and $D_2 = 4$ in.,
   a. Point 1 is never critical;
   b. If $D_1 < 2$ in., then there is no tension;
   c. If $D_1 > 2$ in., point 3 is critical.

4. When $E_1/E_2 = 2$ and $D_2 = 20$ in.,
   a. If $D_1 < 0.33$ in., then there is no tension;
   b. If 0.33 in. $< D_1 < 2.4$ in., then point 1 is critical;
   c. If $D_1 > 2.4$ in. then point 3 is critical.

5. When $E_1/E_2 = 10$, maximum tension is reduced from 207 psi (where $D_2 = 4$ in.) to 166 psi (where $D_2 = 20$ in.).
6. When $E_1/E_2 = 2$, maximum tension is reduced from 24.7 psi (where $D_2 = 4$ in.) to 17.5 psi (where $D_2 = 20$ in.).

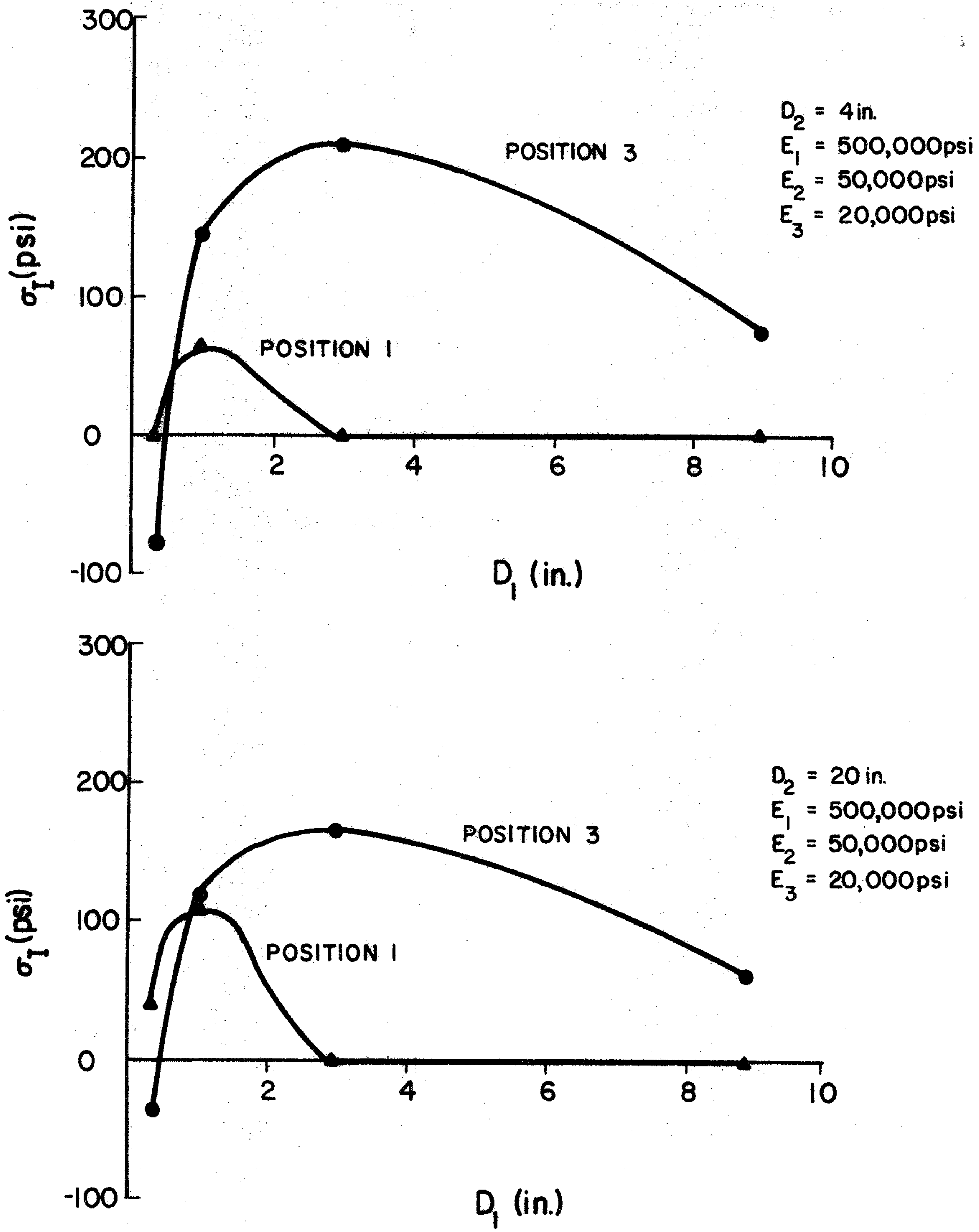

FIG. 2 MAJOR PRINCIPAL STRESS OF PROBLEM 1

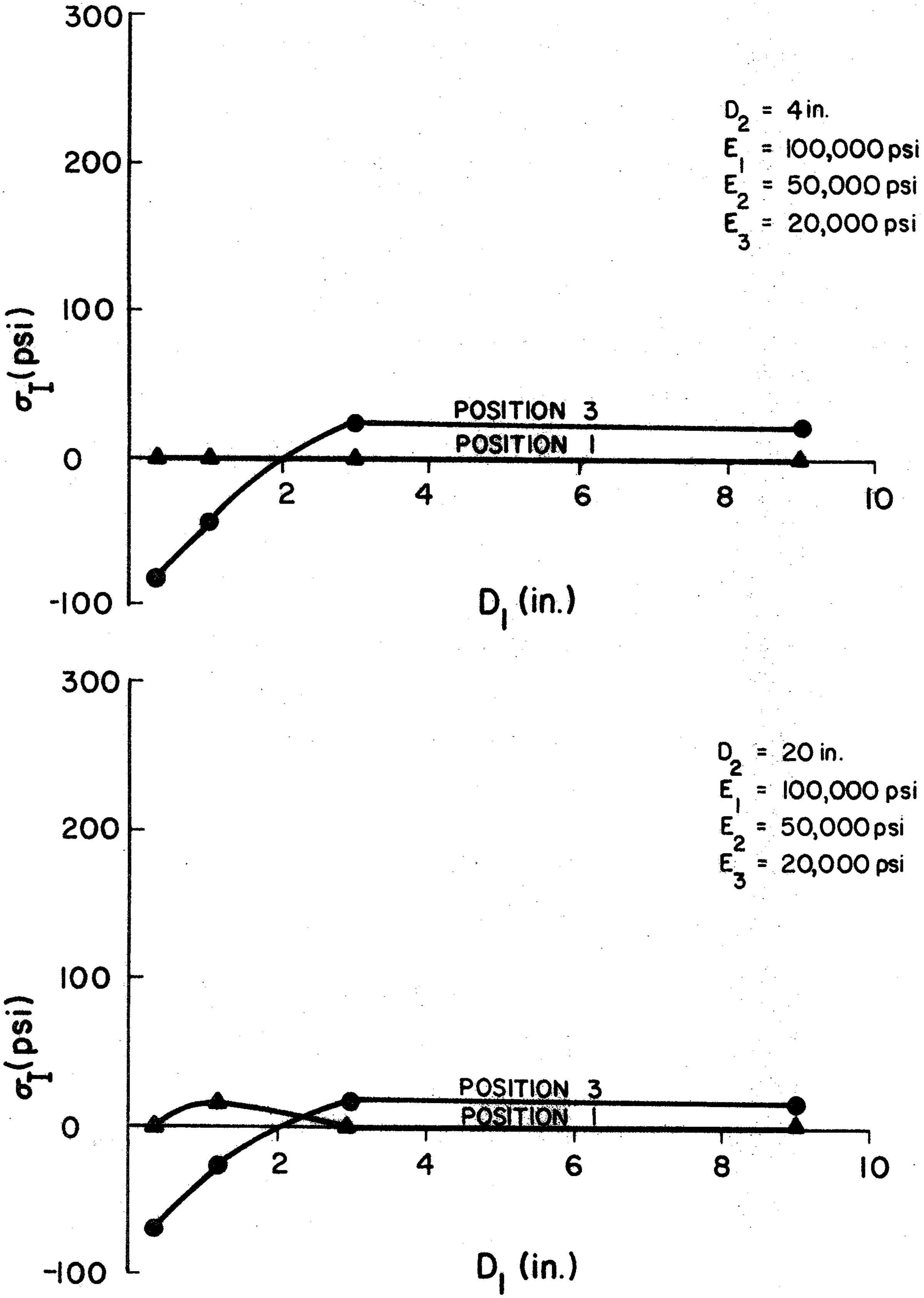

FIG. 2 (CONTINUED)

7. When D_2 = 4 in., maximum tension is reduced from 207 psi (where E_1/E_2 = 10) to 24.7 psi (where E_1/E_2 = 2).

8. When D_2 = 20 in., maximum tension is reduced from 166 psi (where E_1/E_2 = 10) to 17.5 psi (where E_1/E_2 = 2).

In summary, for E_1/E_2 = 10, the tension in HMAC less than 0.5 inches thick appears to be small but increases very rapidly with thickness to peak values at thicknesses of about 3 inches. The tension decreases slowly as HMAC thickness is increased beyond 3 inches. Reducing the E_1/E_2 ratio from 10 to 2 achieves a very important reduction in the peak tension, so that the thickness of HMAC is of little significance in this case.

Figures 3 and 4 are plots, respectively, of the major principal strain and vertical deflection versus surface layer thickness. Since these plots are self-explanatory, no further discussion is included herein. The major concern of this study is the stress, not the strain and deflection.

PROBLEM 2: CRITICAL STRESS ALONG SURFACE

Problem 2 investigates stress, strain and deflection along the pavement surface. The surface is assumed to be very thin. Figure 5 shows the three-layer pavement cross section to be considered. The top layer is the HMAC surface and the bottom layer is the subgrade. Three series of pavement design problems are studied. Material characteristics and layer thicknesses are summarized in Table 4. Series 1 and 2 in Problem 2 use the same

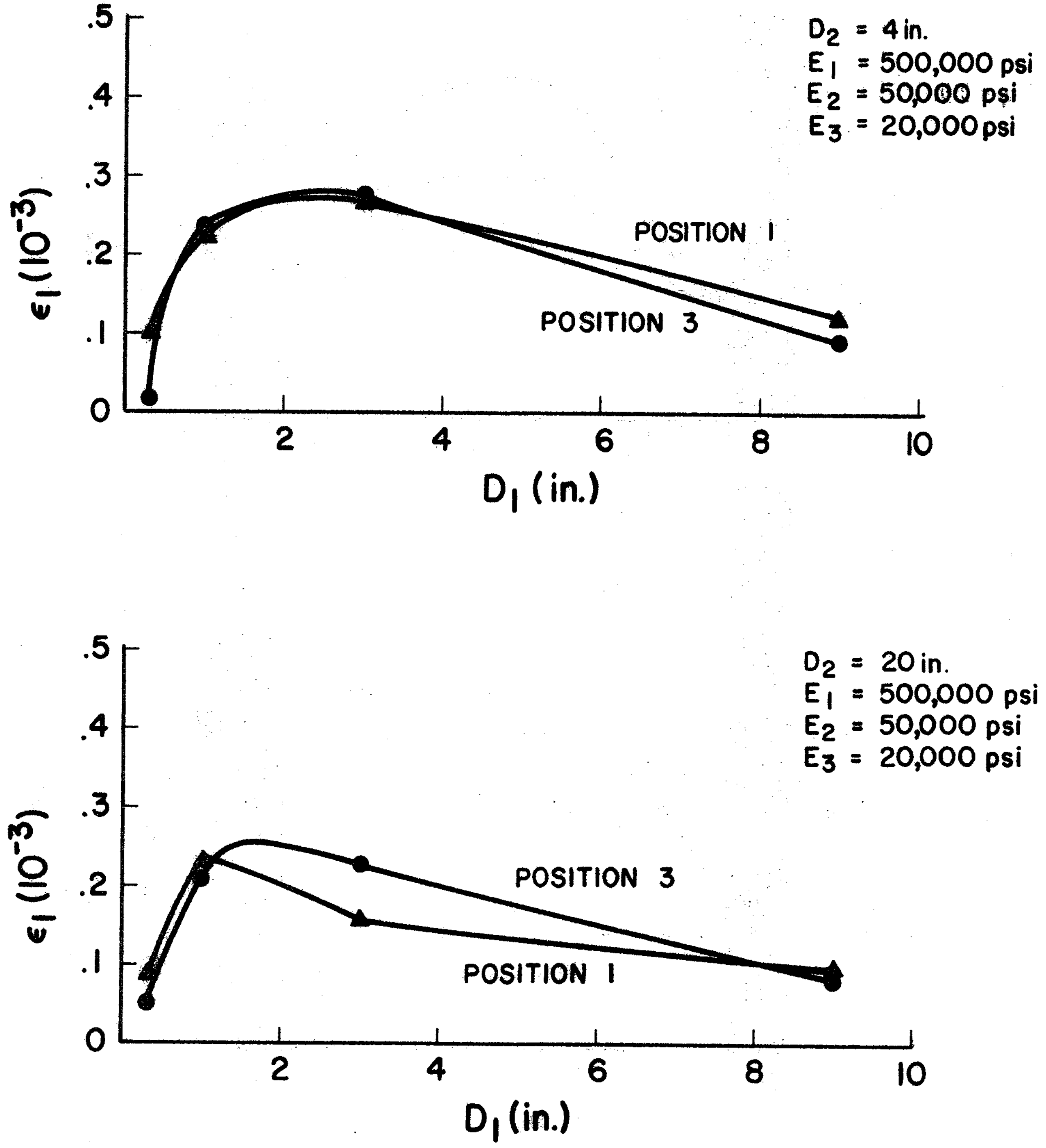

FIG. 3 MAJOR PRINCIPAL STRAIN OF PROBLEM 1

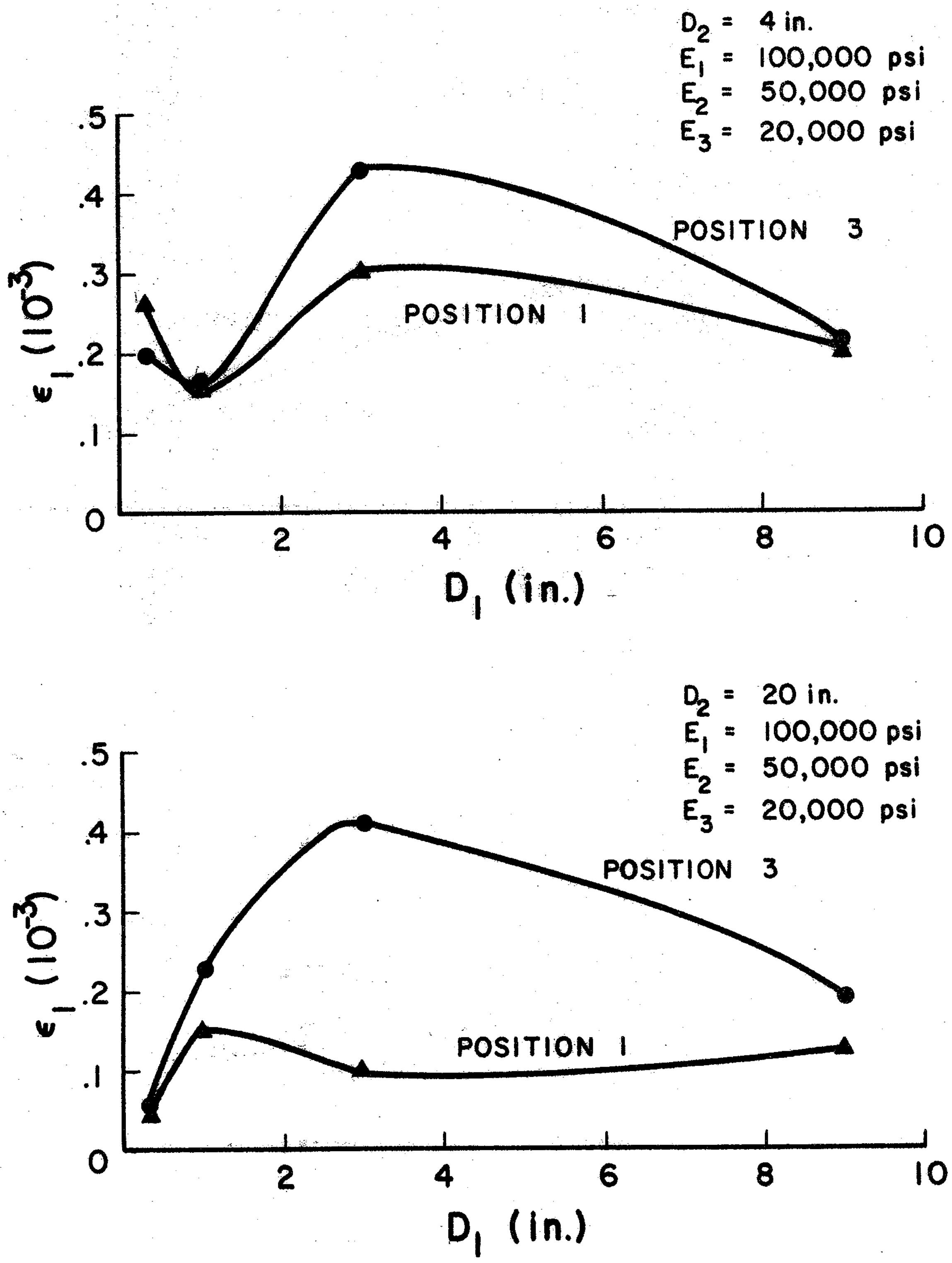

FIG. 3 (CONTINUED)

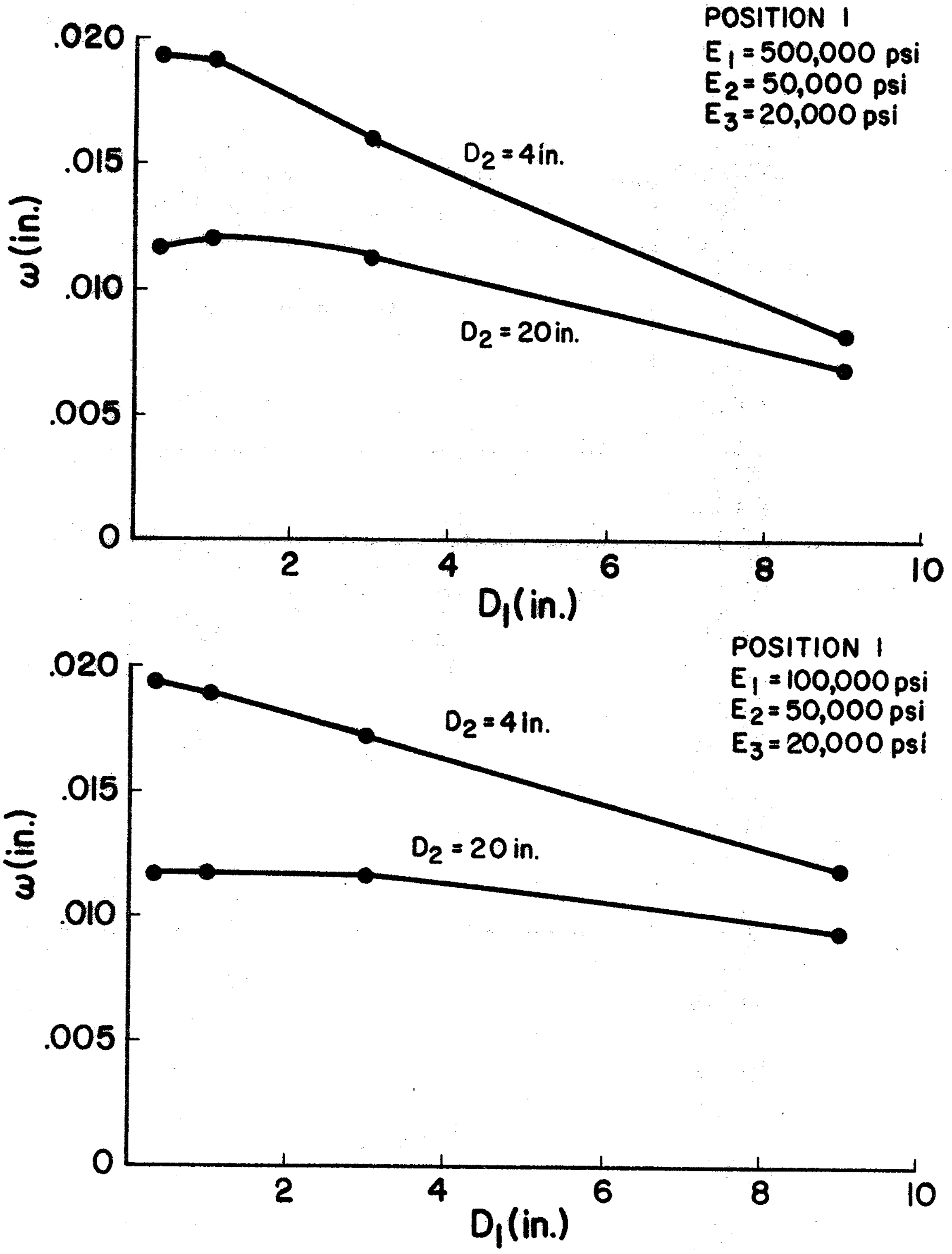

FIG. 4 VERTICAL DEFLECTION OF PROBLEM 1

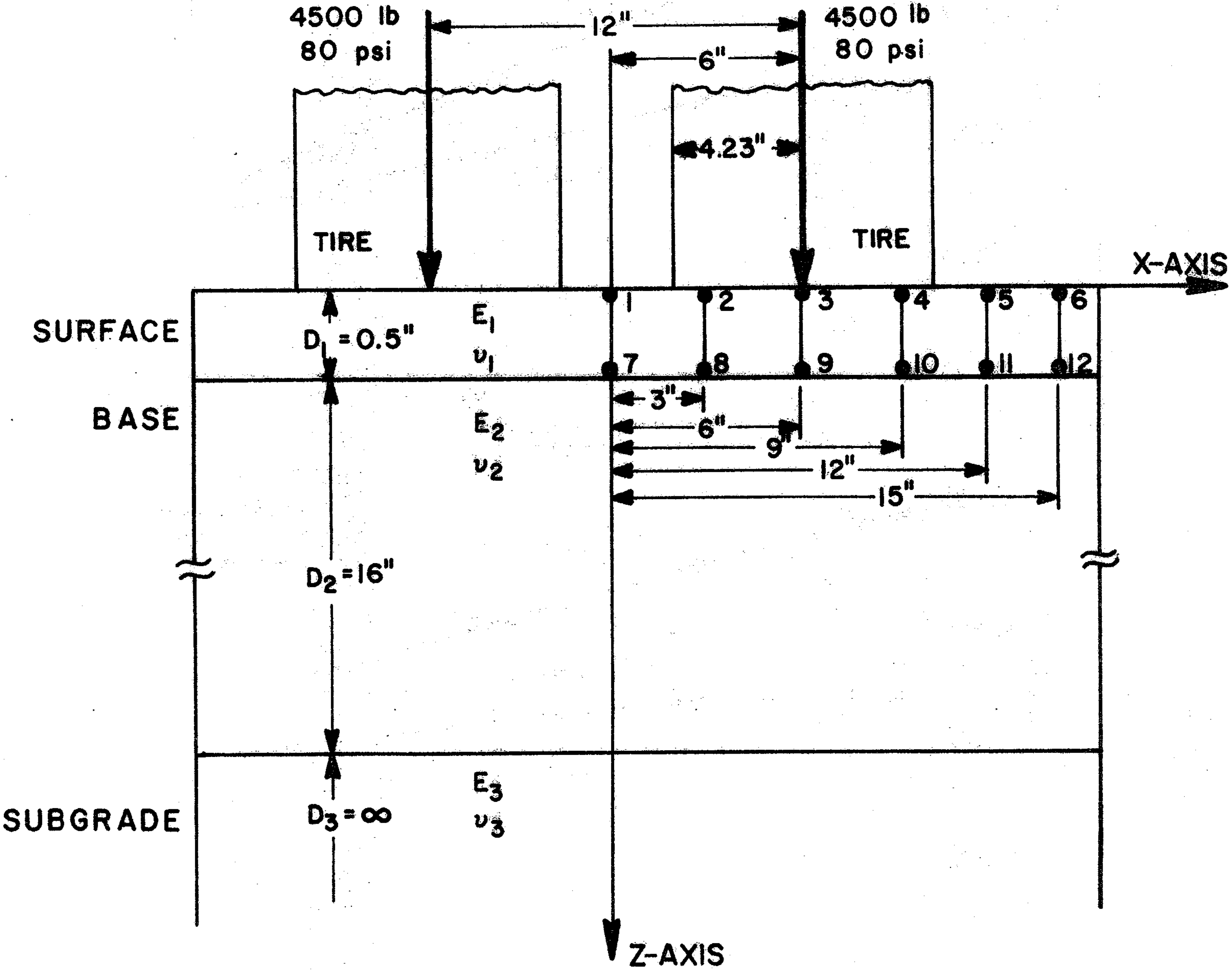

FIG. 5 PAVEMENT STRUCTURE AND DUAL-WHEEL LOADS OF PROBLEM 2

TABLE 4

DESIGN PARAMETERS OF PROBLEM 2

	Surface	Base	Subgrade
Elastic Modulus (psi)	E_1*	50,000	20,000
Poisson's Ratio	0.5	0.5	0.5
Thickness (in.)	0.5	16	---

*E_1 = 500,000 (series 1)
= 100,000 (series 2)
= 50,000 (series 3)

materials as in Problem 1. Series 3 is essentially a two-layer design since $E_1 = E_2 = 50{,}000$ psi. Two 4,500 lb loads are applied to the pavement surface at a uniform pressure of 80 psi over two circular areas, 12 inches center-to-center. Twelve positions, as shown in Figure 5, along the surface in a vertical plane through the truck axle, are evaluated. It must be noted that the X-axis and Z-axis in Figure 5 are not to the same scale.

The previously mentioned streamlined BISTRO program is utilized to solve Problem 2. Outputs are shown in Tables 5, 6 and 7. X is the horizontal distance in inches from the central line (Z - axis) between the dual-wheel loads in the truck axle direction, and Z is the depth in inches below the pavement surface. All positions are within the surface layer, either at the top or at the bottom. σ_I and ε_I represent major principal

TABLE 5

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 2 WHEN $E_1/E_2 = 10$

Position	x(in.)	z(in.)	σ_I (psi)	ε_I	w(in.)
1	0.0	0.0	0.789E 02	0.160E-03	0.0125
2	3.0	0.0	-0.800E 02	0.274E-03	0.0156
3	6.0	0.0	-0.800E 02	0.162E-03	0.0165
4	9.0	0.0	-0.800E 02	0.271E-03	0.0143
5	12.0	0.0	0.351E 02	0.791E-04	0.0093
6	15.0	0.0	0.0	0.270E-04	0.0074
7	0.0	0.5	-0.566E 00	0.206E-03	0.0126
8	3.0	0.5	0.546E 02	0.139E-03	0.0157
9	6.0	0.5	-0.770E 01	0.769E-04	0.0165
10	9.0	0.5	0.684E 02	0.163E-03	0.0143
11	12.0	0.5	-0.233E 00	0.116E-03	0.0093
12	15.0	0.5	0.122E 00	0.440E-04	0.0074

TABLE 6

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 2 WHEN $E_1/E_2 = 2$

Position	x(in.)	z(in.)	σ_I (psi)	ε_I	w(in.)
1	0.0	0.0	0.153E 00	0.353E-04	0.0125
2	3.0	0.0	-0.800E 02	0.206E-03	0.0159
3	6.0	0.0	-0.800E 02	0.120E-03	0.0166
4	9.0	0.0	-0.800E 02	0.191E-03	0.0146
5	12.0	0.0	0.0	0.342E-04	0.0093
6	15.0	0.0	0.0	0.511E-04	0.0074
7	0.0	0.5	-0.704E-01	0.262E-03	0.0126
8	3.0	0.5	-0.472E 02	0.178E-03	0.0159
9	6.0	0.5	-0.630E 02	0.882E-04	0.0166
10	9.0	0.5	-0.428E 02	0.214E-03	0.0145
11	12.0	0.5	0.868E-01	0.151E-03	0.0093
12	15.0	0.5	0.242E-01	0.677E-04	0.0075

TABLE 7

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 2 WHEN $E_1/E_2 = 1$

Position	x(in.)	z(in.)	σ_I (psi)	ε_I	w(in.)
1	0.0	0.0	0.0	0.108E-03	0.0125
2	3.0	0.0	-0.800E 02	0.105E-03	0.0159
3	6.0	0.0	-0.800E 02	0.977E-04	0.0166
4	9.0	0.0	-0.800E 02	0.864E-04	0.0146
5	12.0	0.0	0.0	0.725E-04	0.0093
6	15.0	0.0	0.0	0.576E-04	0.0074
7	0.0	0.5	-0.510E 00	0.288E-03	0.0126
8	3.0	0.5	-0.613E 02	0.205E-03	0.0159
9	6.0	0.5	-0.706E 02	0.955E-04	0.0166
10	9.0	0.5	-0.589E 02	0.245E-03	0.0146
11	12.0	0.5	-0.435E-01	0.169E-03	0.0093
12	15.0	0.5	0.102E-01	0.737E-04	0.0075

stress and strain, respectively. W is the vertical deflection in inches.

Figure 6 shows plots of major principal stresses along the pavement surface at three levels of E_1. Specific findings are as follows:

1. There is no tension or negligible tension (if any) at either the top or the bottom of the HMAC surface layer when the E_1/E_2 ratio equals 2 and 1.
2. For $E_1/E_2 = 10$, it appears that the peak tension at the bottom of the HMAC is high (near 70 psi), and is located not under the center of the tire but between the center and the outer edge. Another peak tension at the bottom of the HMAC (near 55 psi) is located between the center and the inner edge of the tire.
3. An even higher tension (near 80 psi) exists, for $E_1/E_2 = 10$, at the top of the HMAC between two tires (where $x = Z = 0$). However, the stress at the position between the two tires but at the bottom of the HMAC (where $x = 0$ and $Z = 0.5$) is negligible.
4. For all three levels of the E_1/E_2 ratio, the compression at the top of the HMAC increases very rapidly with x (where $0 \leq X \leq 1.77$) to 80 psi at the inner edge of the tire. The compression is 80 psi from the inner edge to the outer edge ($1.77 \leq X \leq 10.23$), and decreases very rapidly as X is increased beyond the outer edge ($X \geq 10.23$).

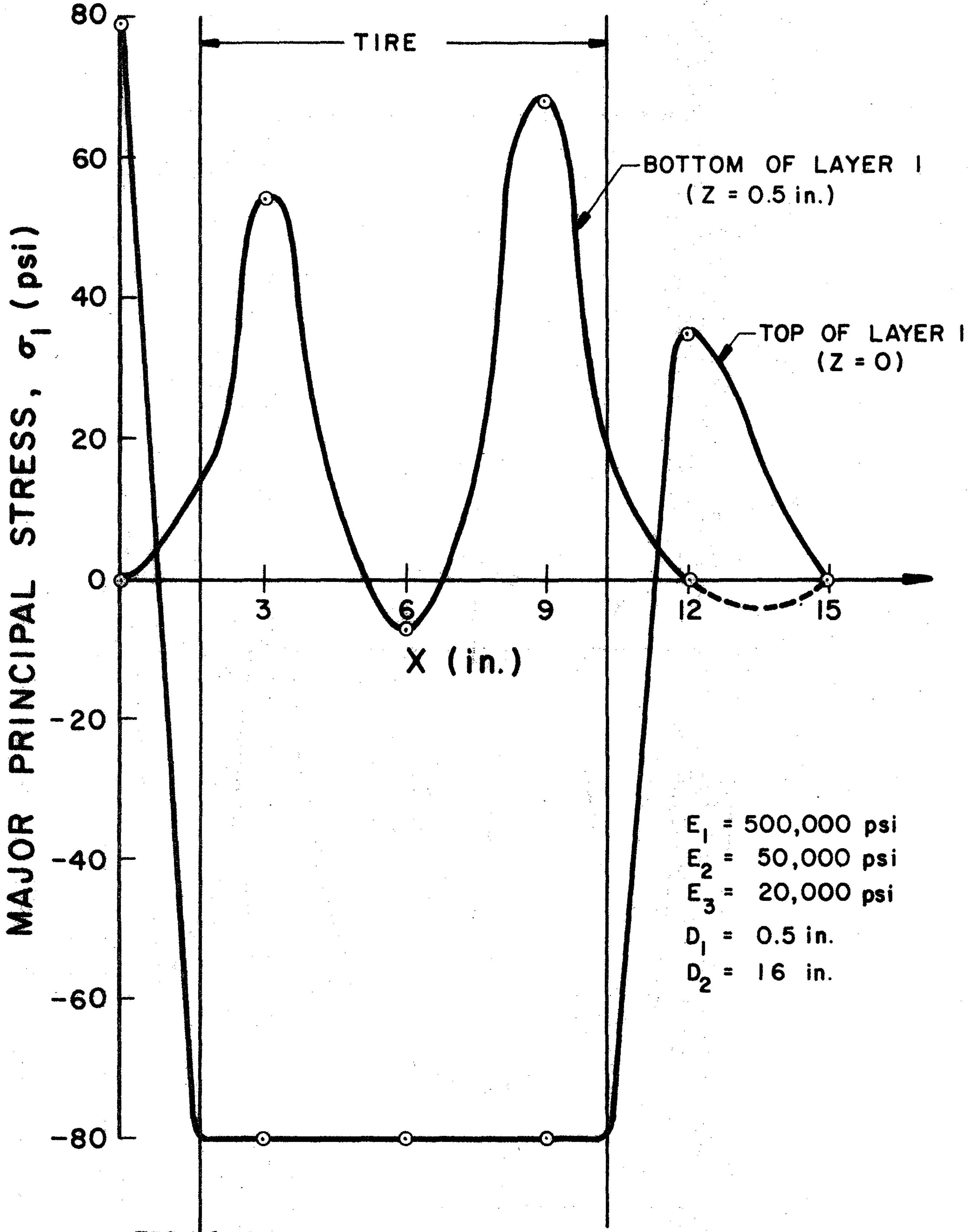

FIG. 6 MAJOR PRINCIPAL STRESS OF PROBLEM 2

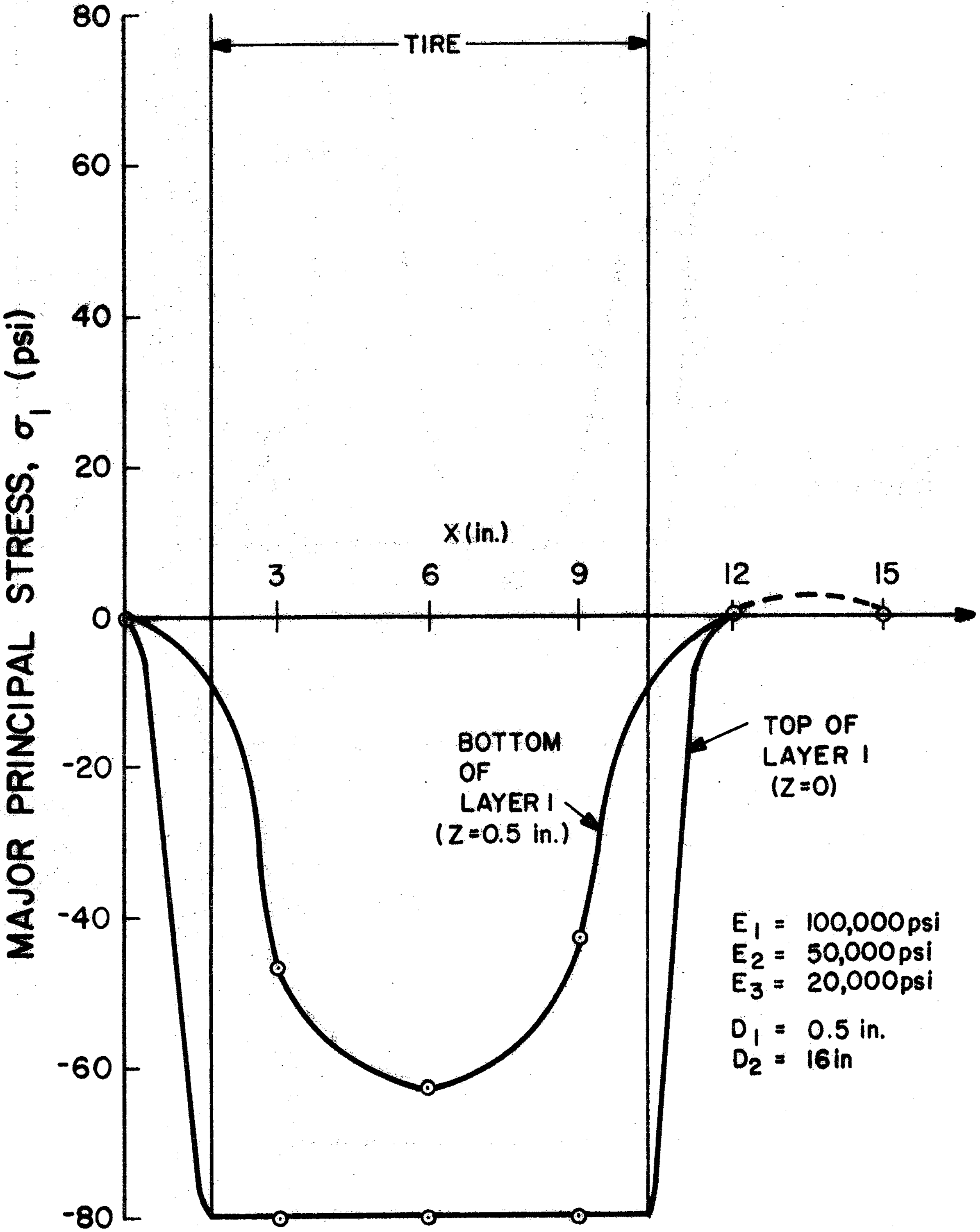

FIG. 6 (CONTINUED)

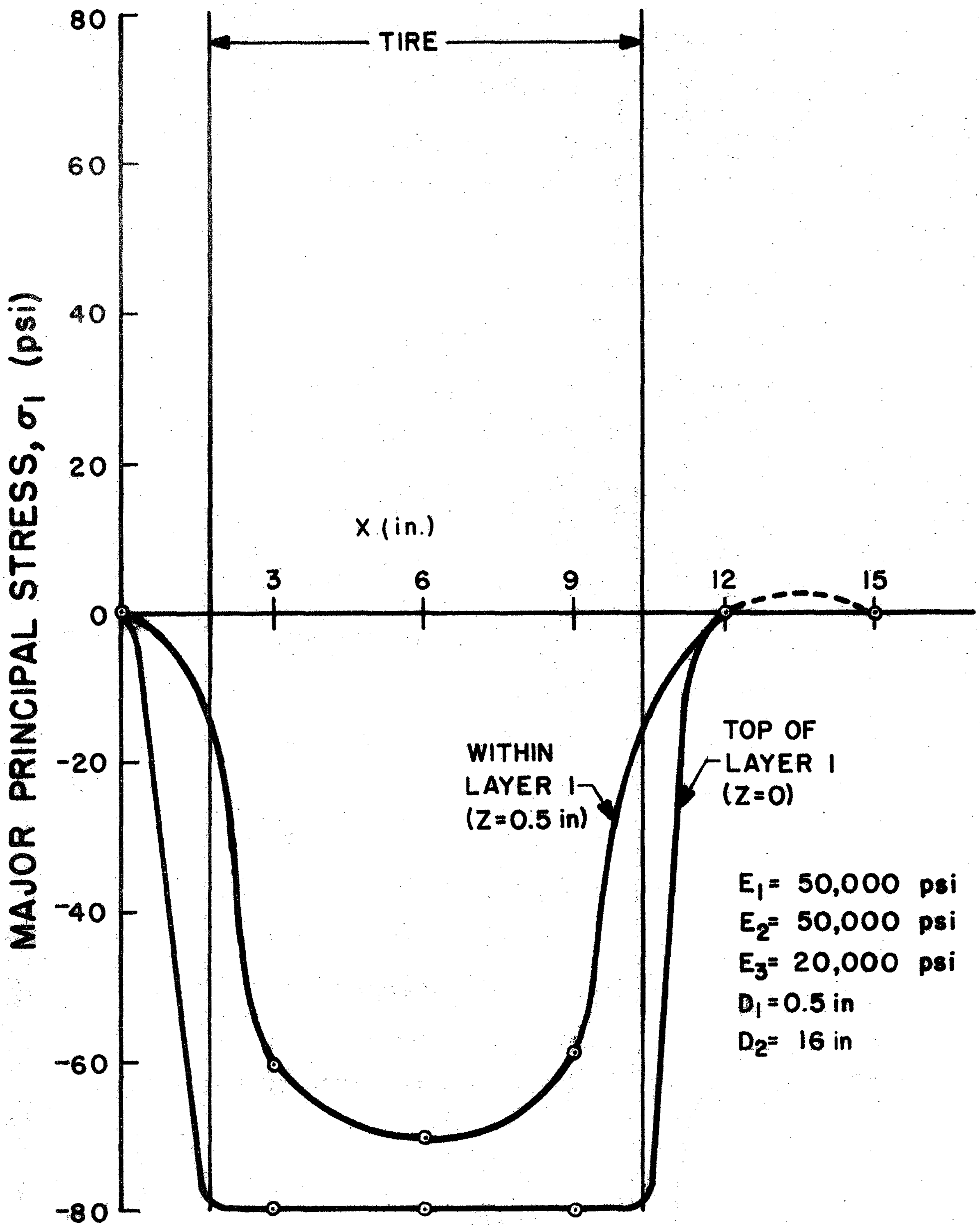

FIG. 6 (CONTINUED)

5. For $E_1/E_2 = 2$ and $E_1/E_2 = 1$, there is no stress or negligible stress (either tension or compression) at positions 1, 5, 7 and 11; For $E_1/E_2 = 10$, the compression at positions 7 and 11 is also negligible.
6. For $E_1/E_2 = 2$ and $E_1/E_2 = 1$, the compression at the bottom of the HMAC increases with X to a peack value at the center of the tire and then decreases with X beyond the center.
7. Maximum tension at the top of the HMAC is reduced from near 80 psi to a negligible value when the E_1/E_2 ratio is reduced from 10 to 2 and 1.
8. Maximum compression at the top of the HMAC is 80 psi for all three series.
9. Maximum tension at the bottom of the HMAC is reduced from near 70 psi to no tension when the E_1/E_2 ratio is reduced from 10 to 2 and 1.
10. Maximum compression at the bottom of the HMAC is increased from about 8 psi to 63 psi and 71 psi when the E_1/E_2 ratio is reduced from 10 to 2 and 1, respectively.

Major principal strain and vertical deflection along the pavement surface are also plotted, respectively, in Figures 7 and 8. It has been found that the HMAC modulus has negligible effects on the pavement deflection since the HMAC surface is very thin, the deflection basin at the top and the bottom of the surface layer is almost identical.

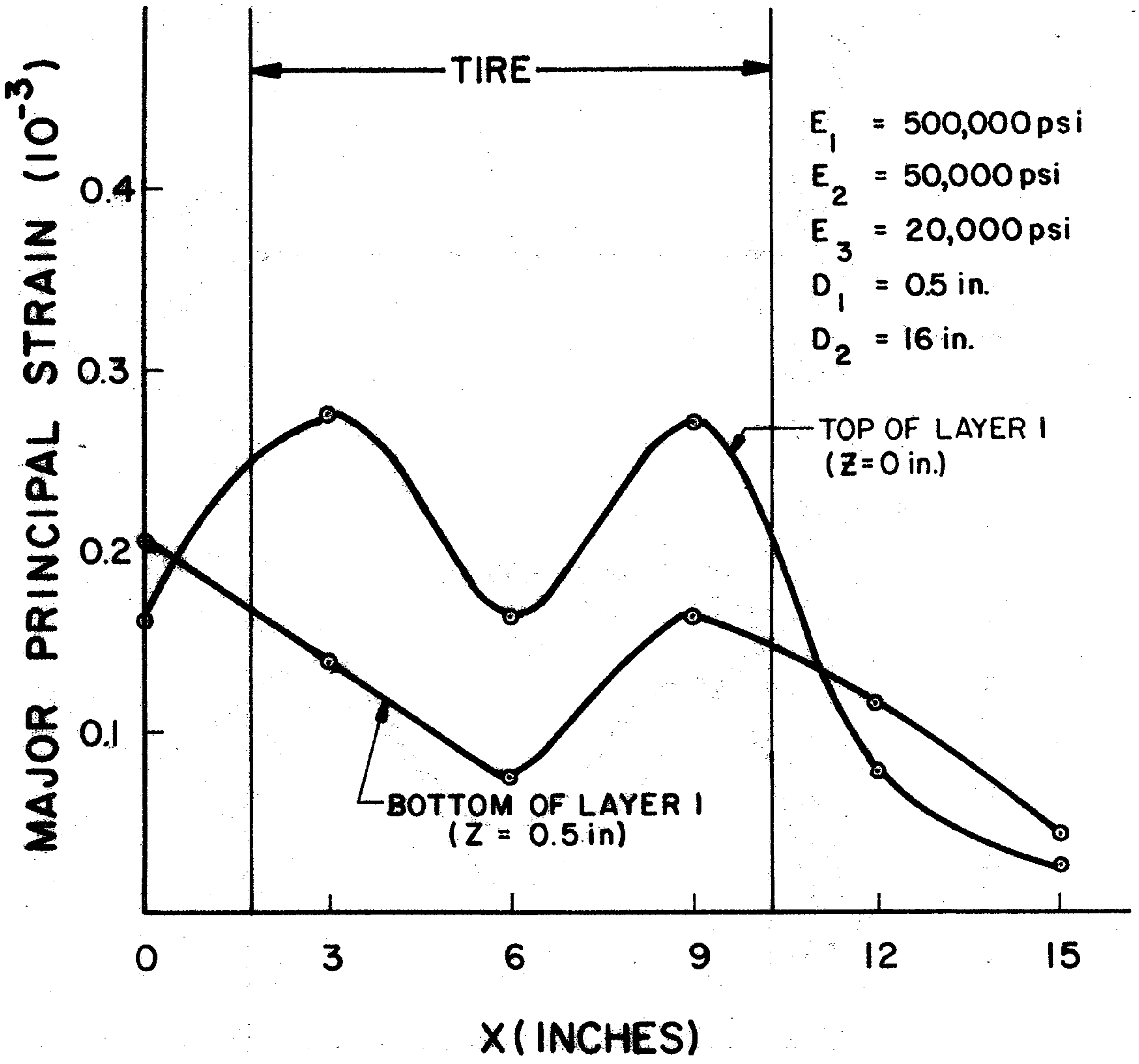

FIG. 7 MAJOR PRINCIPAL STRAIN OF PROBLEM 2

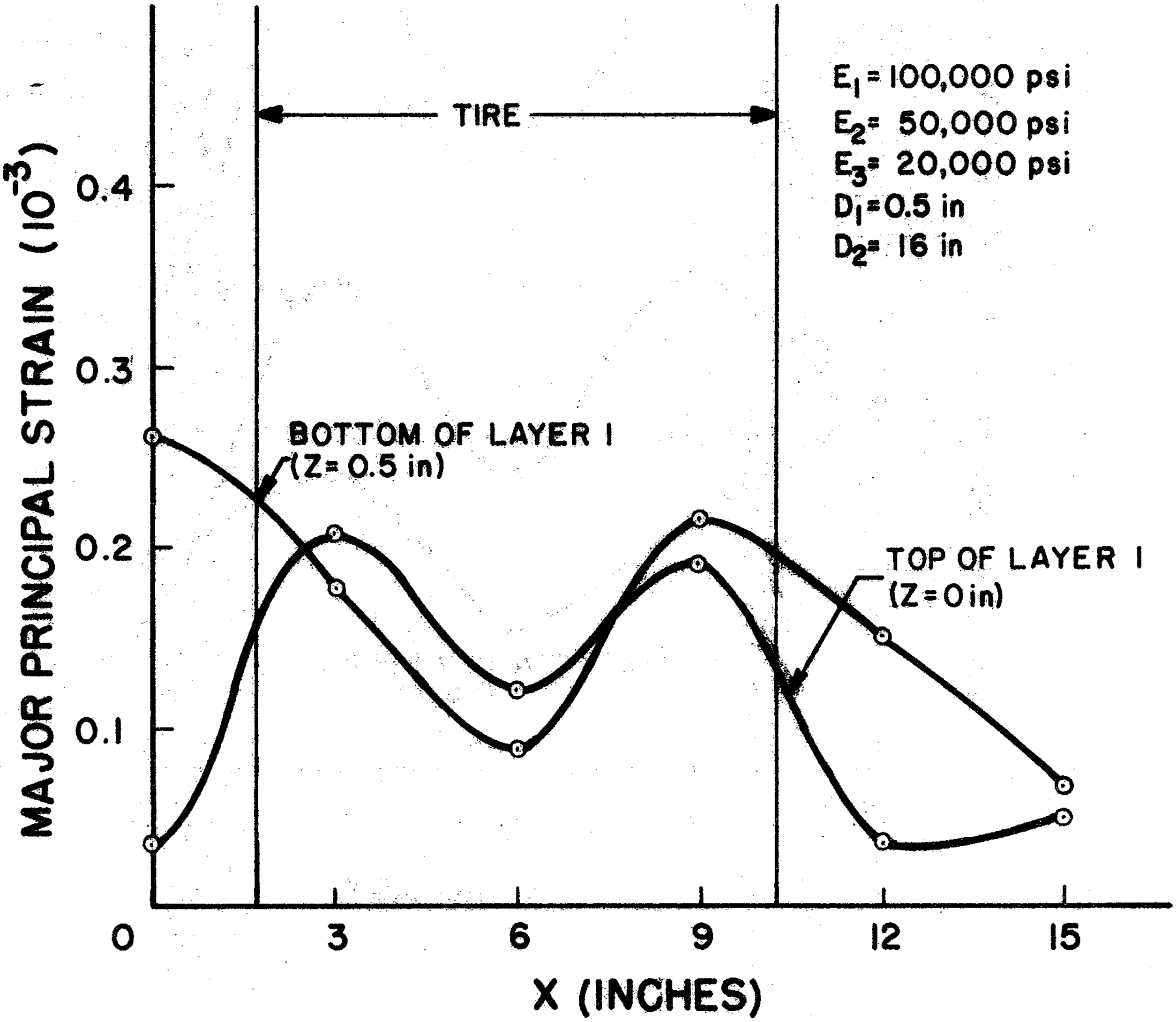

FIG. 7 (CONTINUED)

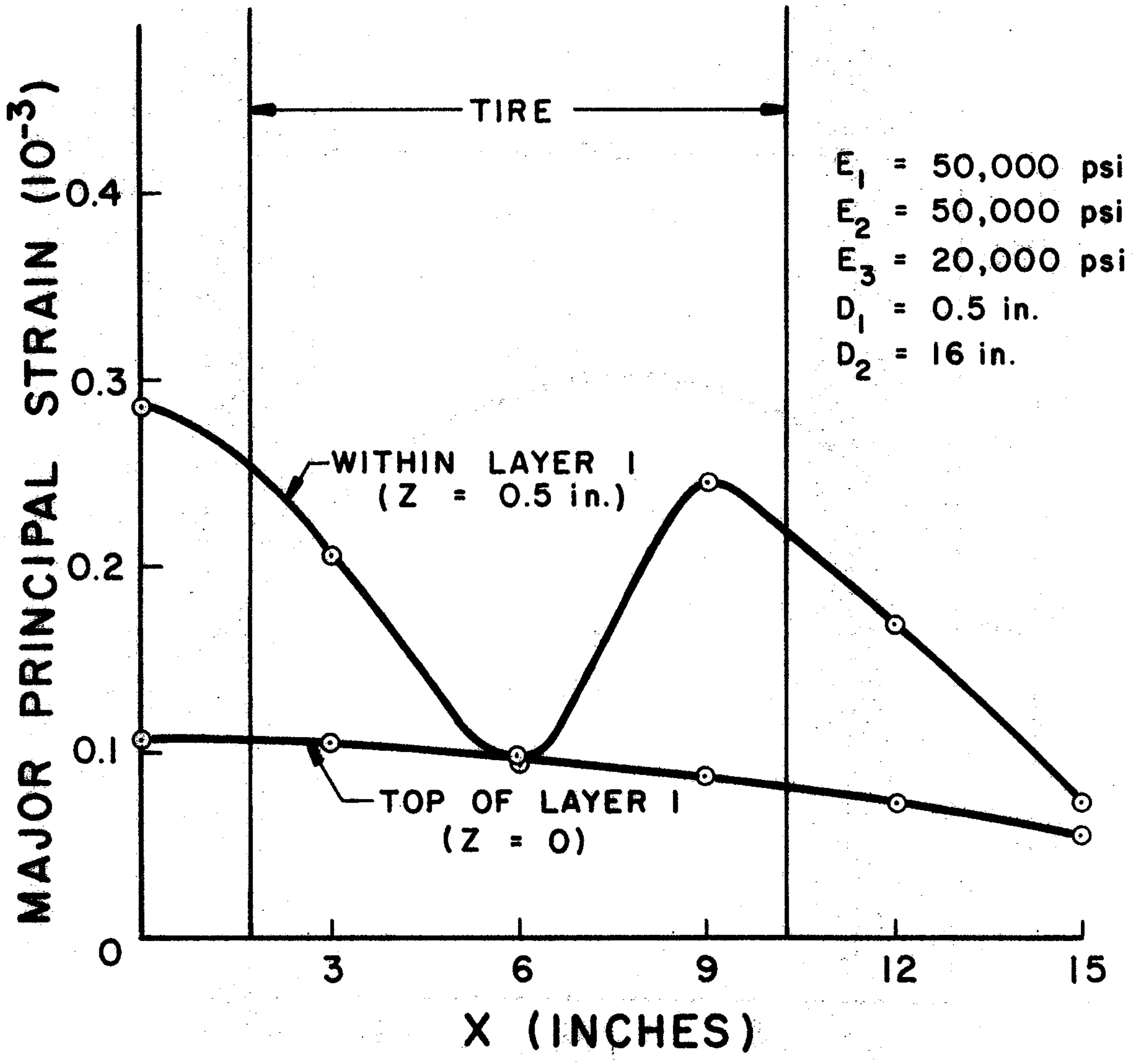

FIG. 7 (CONTINUED)

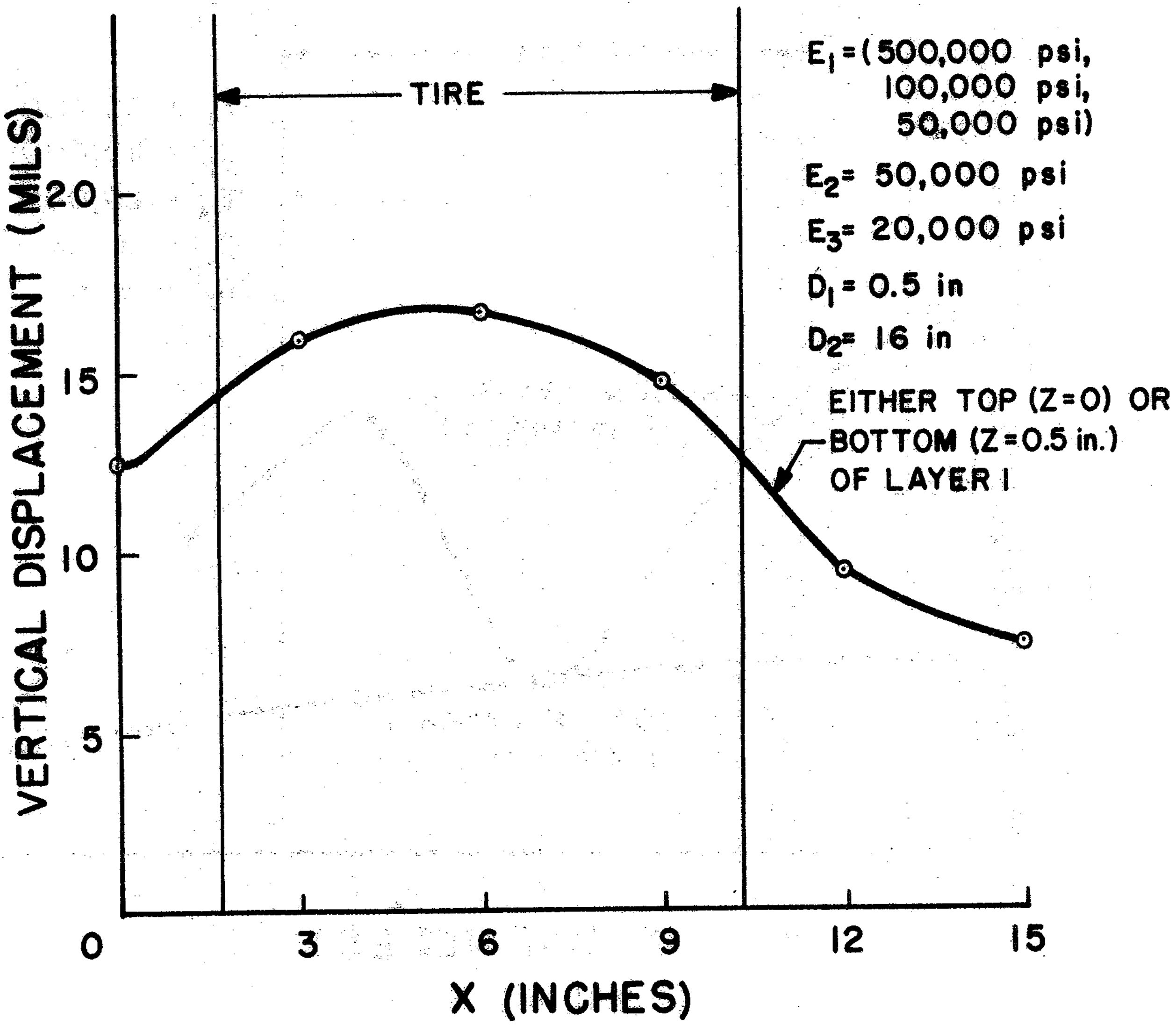

FIG. 8 VERTICAL DEFLECTION OF PROBLEM 2

PROBLEM 3: SOFTENING OF BASE MATERIAL

Problem 3 treats softening of base material immediately under the surface layer. The sketch in Figure 9 represents the pavement cross-section composed of four layers. The top layer is the HMAC surface and is three inches thick. The second layer is assumed to be very thin (0.5 inches) and has five levels of elastic modulus value: 50,000, 25,000, 12,500, 6,250 and 3,125 psi. The third layer is 15.5 inches thick such that the composite thickness of the second and third layer is equal to the thickness of the second layer (16 inches) in Problem 2. The fourth layer, the bottom layer, is the subgrade and has infinite thickness. Design parameters are summarized in Table 8.

TABLE 8

DESIGN PARAMETERS OF PROBLEM 3

	Surface	Base	Subbase	Subgrade
Elastic Modulus (psi)	E_1*	E_2**	50,000	20,000
Poisson's Ratio	0.5	0.5	0.5	0.5
Thickness (in.)	3.0	0.5	15.5	---

*E_1 = 500,000 (series 1)
= 100,000 (series 2)

**E_2 has five levels for each series: 50,000, 25,000, 12,500, 6,250 and 3,125.

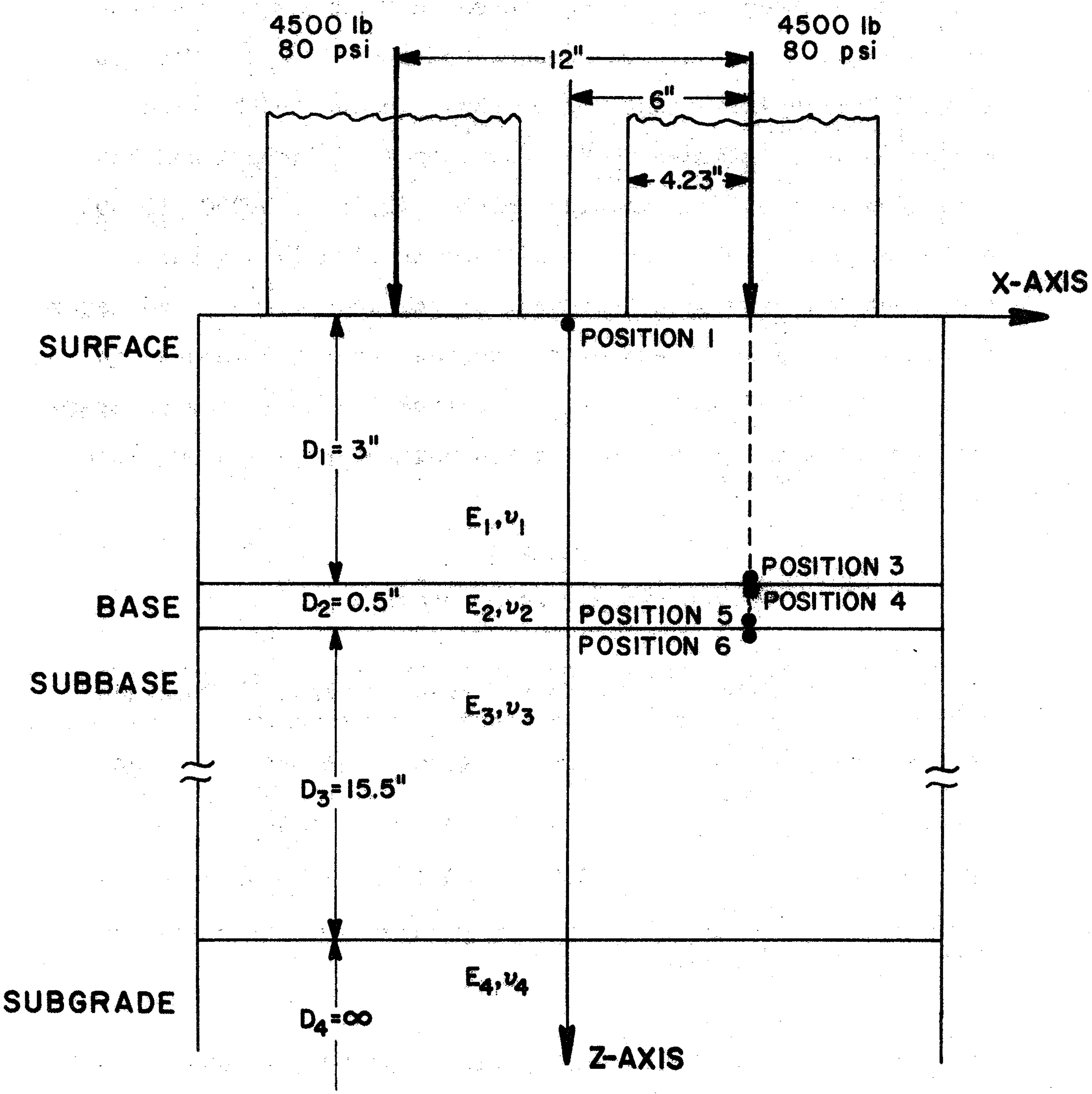

FIG. 9 PAVEMENT STRUCTURE AND DUAL-WHEEL LOADS OF PROBLEM 3

As shown in Figure 9, two 4,500 lb loads are assumed to be distributed at a uniform pressure of 80 psi over two circular areas, 12 inches center-to-center. Six positions are investigated in this problem. Position 1 is at the top of the HMAC, between two loads, that is, the intersection of the X-axis and the Z-axis. The Y-axis, which is not shown in the figure, is perpendicular to the X-Z plane and passes through position 1. Position 2 is on the Y-axis, 12 inches from position 1. Positions 3, 4, 5 and 6 are layer interfacial points under one of the dual-wheel loads. Position 3 is at the bottom of the HMAC. Positions 4 and 5 are at the top and the bottom of the base course, respectively. Position 6 is at the top of the subbase course. The scale of Z-axis in Figure 9 is three times of the scale of X-axis such that the positions under investigation can be seen clearly.

Again, the streamlined BISTRO program is utilized to analyze Problem 3. Outputs are shown in Tables 9 and 10.

In Figure 10 are plots of the major principal stress, σ_I, versus the elastic modulus of the second layer at four layer interfacial positions. Specific findings are as follows:

1. Maximum tension exists at position 3, the bottom of the HMAC. Positions 4, 5 and 6 are compressed.
2. Tension at position 3 and compression at positions 4, 5 and 6 decreases in convex shape when the elastic modulus of the second layer increases.

TABLE 9

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 3 (SERIES 1)

E_2 (psi)	X(in.)	y(in.)	Z(in.)	Layer	σ_I (psi)	ε_I	w(in.)
50,000	0.0	0.0	0.0	1	--	--	0.0119
	0.0	12.00	0.0	1	--	--	0.0072
	6.00	0.0	3.00	1	0.168E 03	0.229E-03	0.0120
	6.00	0.0	3.00	2	-0.165E 02	0.229E-03	0.0120
	6.00	0.0	3.50	2	-0.136E 02	0.239E-03	0.0118
	6.00	0.0	3.50	3	-0.136E 02	0.239E-03	0.0118
25,000	0.0	0.0	0.0	1	--	--	0.0120
	0.0	12.00	0.0	1	--	--	0.0072
	6.00	0.0	3.00	1	0.179E 03	0.241E-03	0.0121
	6.00	0.0	3.00	2	-0.264E 02	0.241E-03	0.0121
	6.00	0.0	3.50	2	-0.262E 02	0.209E-03	0.0119
	6.00	0.0	3.50	3	-0.169E 02	0.209E-03	0.0119
12,500	0.0	0.0	0.0	1	--	--	0.0121
	0.0	12.00	0.0	1	--	--	0.0073
	6.00	0.0	3.00	1	0.189E 03	0.252E-03	0.0122
	6.00	0.0	3.00	2	-0.317E 02	0.252E-03	0.0122
	6.00	0.0	3.50	2	-0.321E 02	0.208E-03	0.0120
	6.00	0.0	3.50	3	-0.213E 02	0.168E-03	0.0120
6,250	0.0	0.0	0.0	1	--	--	0.0123
	0.0	12.00	0.0	1	--	--	0.0073
	6.00	0.0	3.00	1	0.198E 03	0.263E-03	0.0124
	6.00	0.0	3.00	2	-0.345E 02	0.290E-03	0.0124
	6.00	0.0	3.50	2	-0.345E 02	0.326E-03	0.0122
	6.00	0.0	3.50	3	-0.261E 02	0.121E-03	0.0122
3,125	0.0	0.0	0.0	1	--	--	0.0125
	0.0	12.00	0.0	1	--	--	0.0074
	6.00	0.0	3.00	1	0.207E 03	0.273E-03	0.0125
	6.00	0.0	3.00	2	-0.359E 02	0.361E-03	0.0125
	6.00	0.0	3.50	2	-0.358E 02	0.509E-03	0.0124
	6.00	0.0	3.50	3	-0.303E 02	0.779E-04	0.0124

TABLE 10

ANALYSIS OF LINEAR ELASTICITY OF PROBLEM 3 (SERIES 2)

E_2 (psi)	X(in.)	Y(in.)	Z(in.)	Layer	σ_I (psi)	ε_I	w(in.)
50,000	0.0	0.0	0.0	1	--	--	0.0123
	0.0	12.00	0.0	1	--	--	0.0070
	6.00	0.0	3.00	1	0.171E 02	0.407E-03	0.0139
	6.00	0.0	3.00	2	-0.205E 02	0.407E-03	0.0139
	6.00	0.0	3.50	2	-0.161E 02	0.410E-03	0.0136
	6.00	0.0	3.50	3	-0.161E 02	0.410E-03	0.0136
25,000	0.0	0.0	0.0	1	--	--	0.0124
	0.0	12.00	0.0	1	--	--	0.0070
	6.00	0.0	3.00	1	0.295E 02	0.477E-03	0.0141
	6.00	0.0	3.00	2	-0.370E 02	0.477E-03	0.0141
	6.00	0.0	3.50	2	-0.378E 02	0.384E-03	0.0137
	6.00	0.0	3.50	3	-0.202E 02	0.384E-03	0.0127
12,500	0.0	0.0	0.0	1	--	--	0.0126
	0.0	12.00	0.0	1	--	--	0.0070
	6.00	0.0	3.00	1	0.423E 02	0.551E-03	0.0143
	6.00	0.0	3.00	2	-0.474E 02	0.551E-03	0.0143
	6.00	0.0	3.50	2	-0.499E 02	0.327E-03	0.0139
	6.00	0.0	3.50	3	-0.275E 02	0.327E-03	0.0139
6,250	0.0	0.0	0.0	1	--	--	0.0128
	0.0	12.00	0.0	1	--	--	0.0070
	6.00	0.0	3.00	1	0.550E 02	0.624E-03	0.0145
	6.00	0.0	3.00	2	-0.540E 02	0.624E-03	0.0145
	6.00	0.0	3.50	2	-0.560E 02	0.338E-03	0.0141
	6.00	0.0	3.50	3	-0.362E 02	0.252E-03	0.0141
3,125	0.0	0.0	0.0	1	--	--	0.0131
	0.0	12.00	0.0	1	--	--	0.0070
	6.00	0.0	3.00	1	0.665E 02	0.691E-03	0.0148
	6.00	0.0	3.00	2	-0.579E 02	0.691E-03	0.0148
	6.00	0.0	3.50	2	-0.590E 02	0.496E-03	0.0143
	6.00	0.0	3.50	3	-0.442E 02	0.180E-03	0.0143

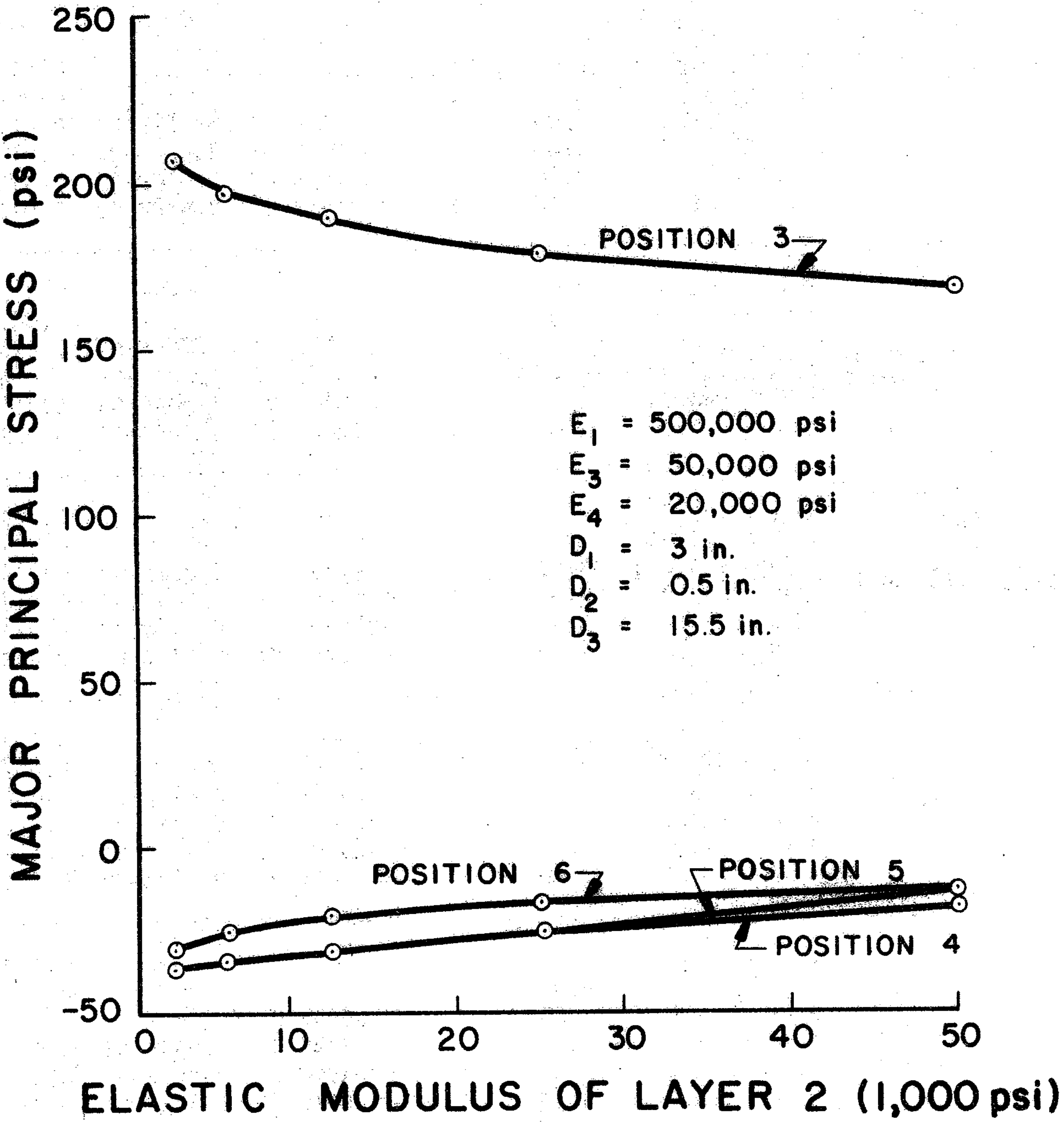

FIG. 10 MAJOR PRINCIPAL STRESS OF PROBLEM 3

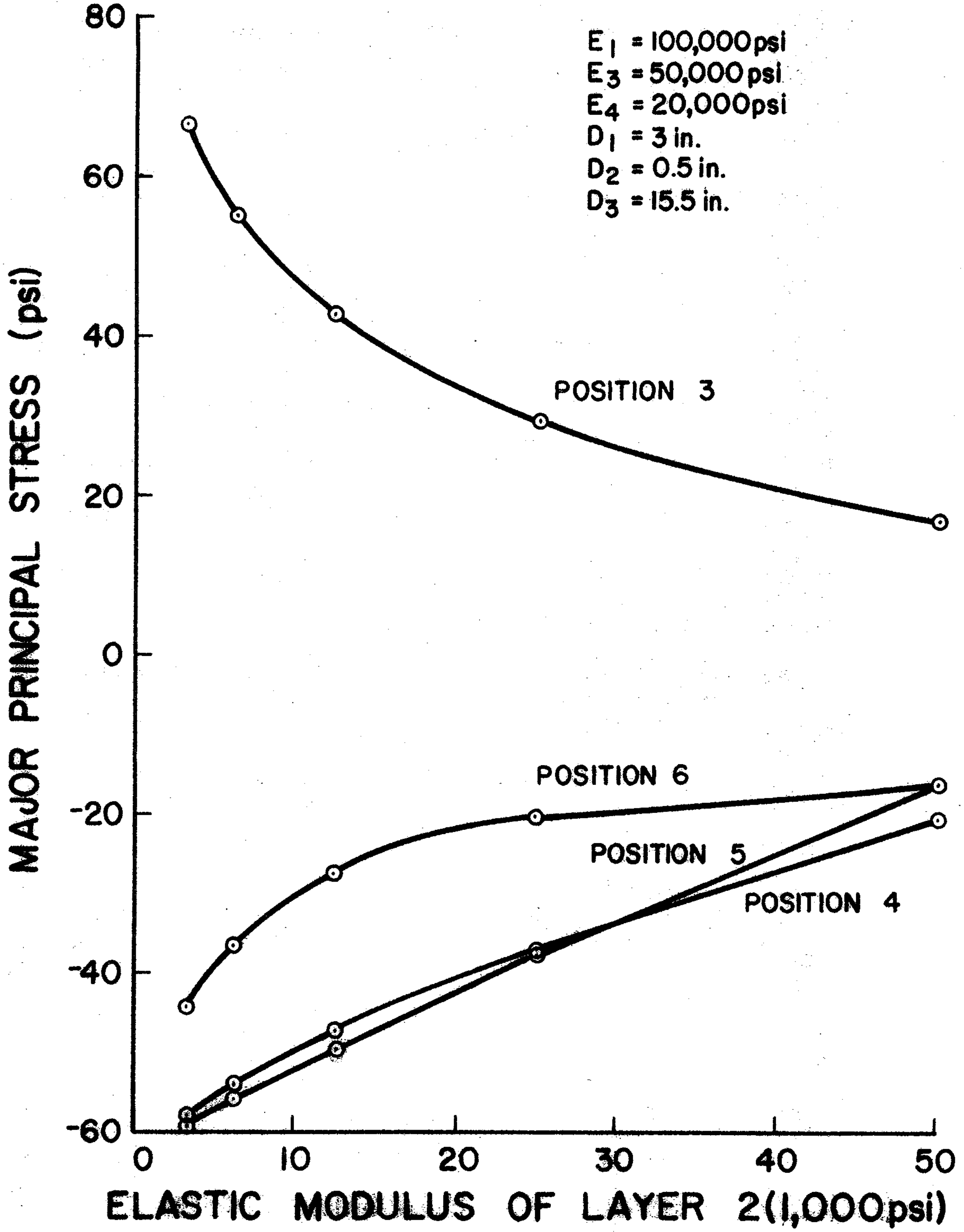

FIG. 10 (CONTINUED)

3. For E_2 = 3,125 psi, tension at position 3 is reduced from 207 psi to 66.5 psi when E_1 is reduced from 500,000 psi to 100,000 psi. For E_2 = 50,000 psi, tension at position 3 is reduced from 168 psi to 17.1 psi when E_1 is reduced from 500,000 psi to 100,000 psi.
4. For E_1 = 500,000 psi, the variation of compression at positions 4, 5 and 6 is within 10 psi. For E_1 = 100,000 psi, the maximum variation is more than 20 psi.
5. Except at position 5, the variation of stress (either tension or compression) is smoother when E_2 is greater than 25,000 psi. Compression at position 5 decreases linearly when E_2 increases.

Major principal strain and vertical deflection versus the elastic modulus of the base course are shown, respectively, in Figures 11 and 12 at two levels of E_1.

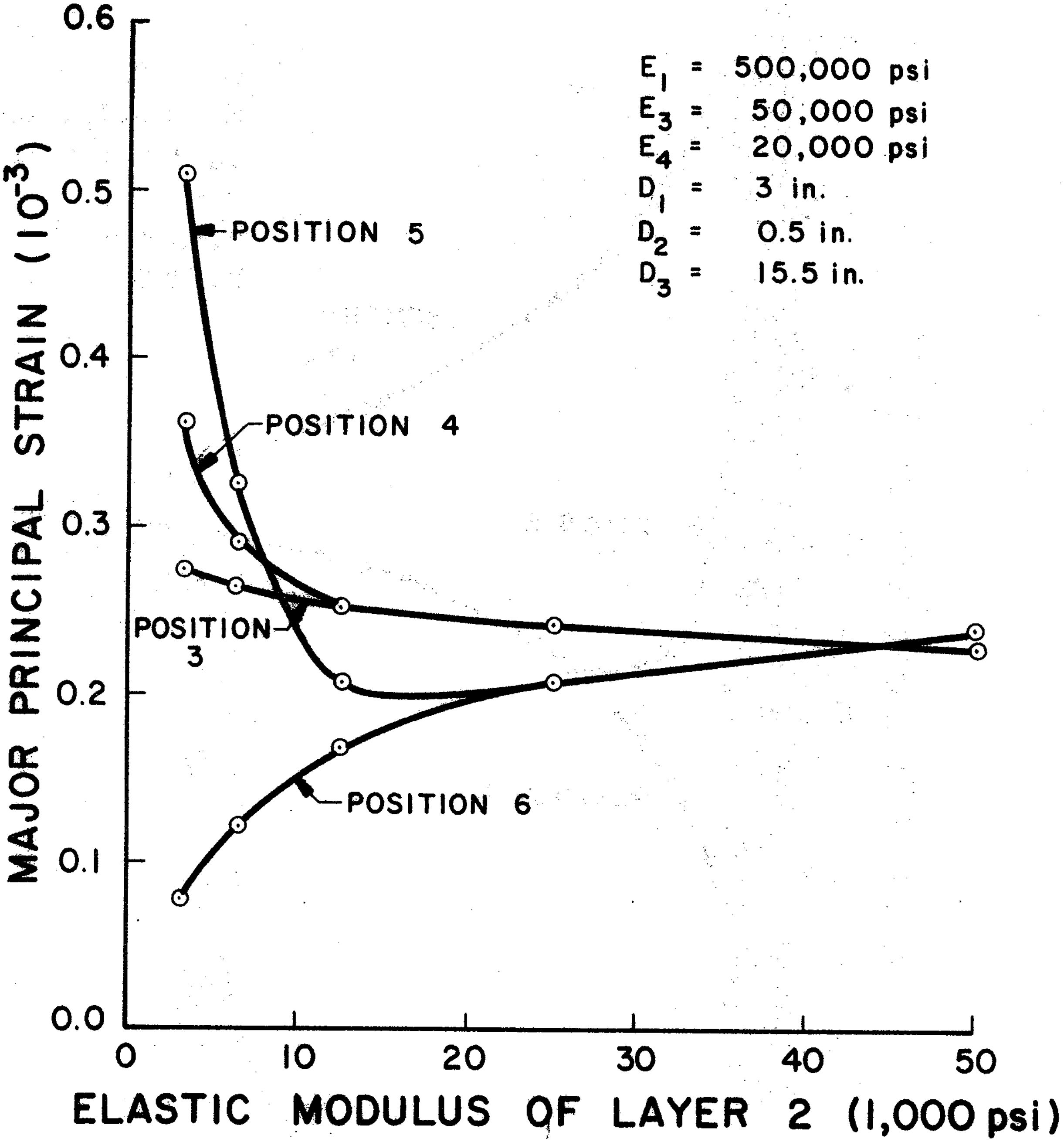

FIG. 11 MAJOR PRINCIPAL STRAIN OF PROBLEM 3

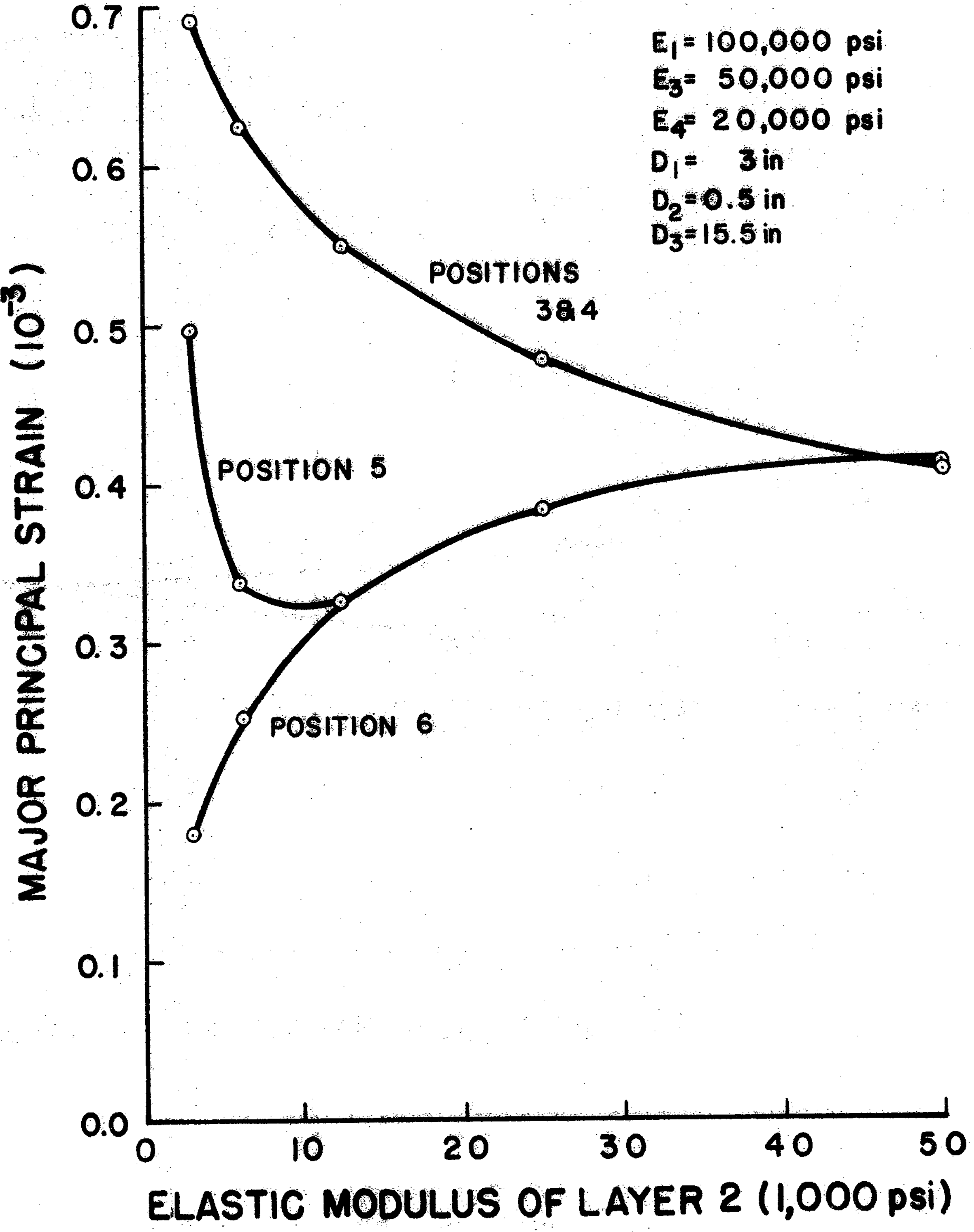

FIG. 11 (CONTINUED)

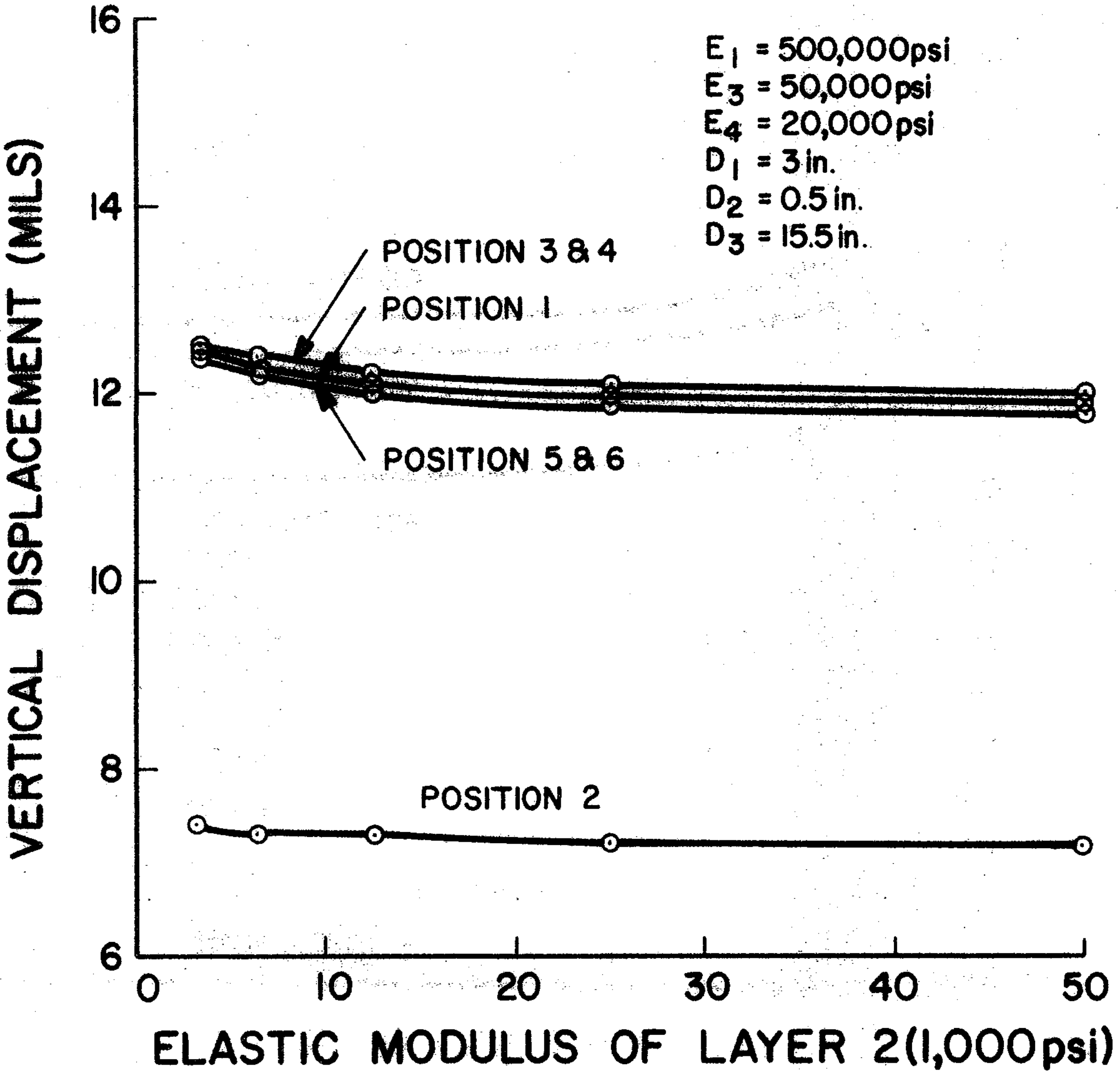

FIG. 12 VERTICAL DEFLECTION OF PROBLEM 3

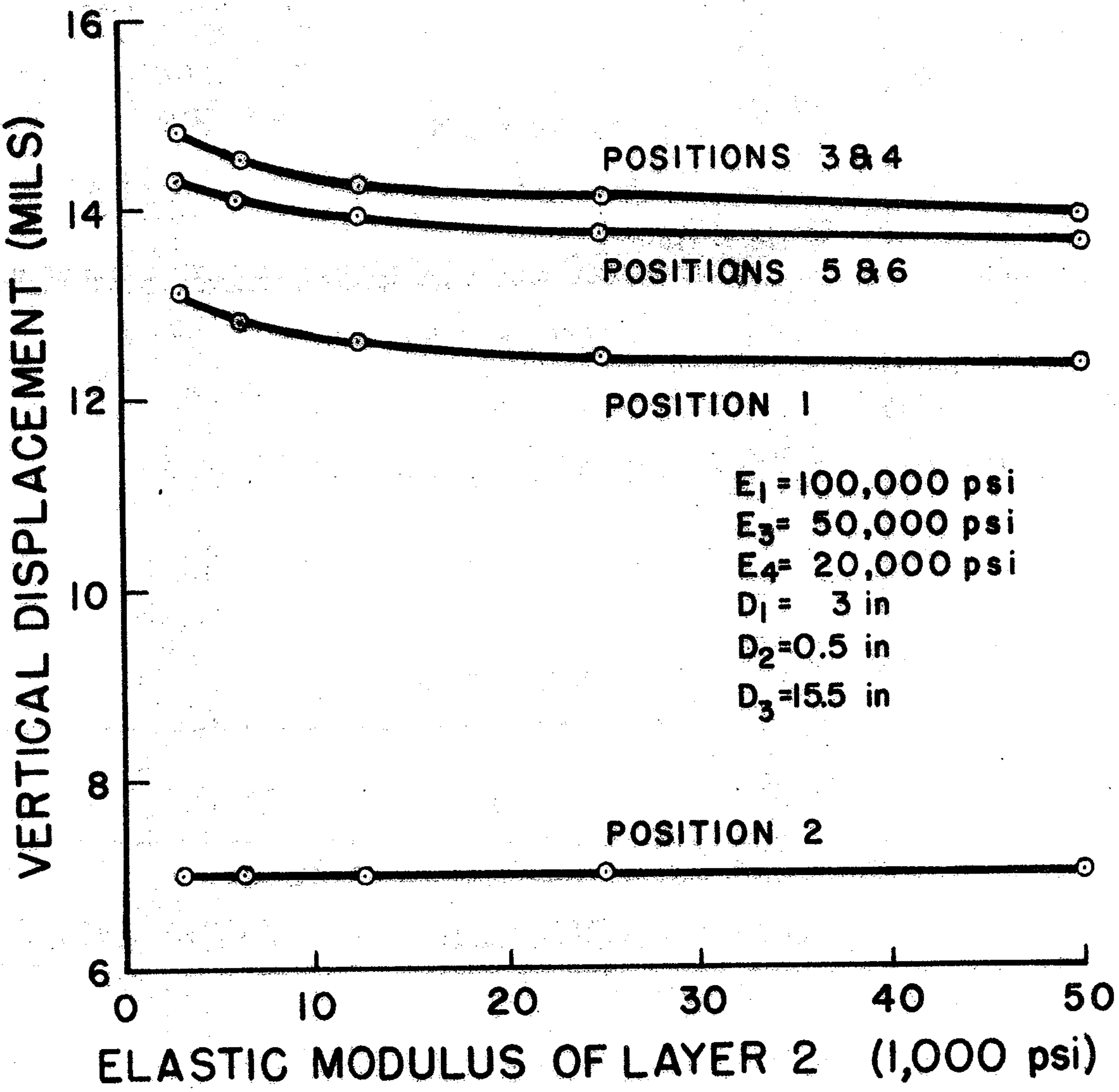

FIG. 12 (CONTINUED)

APPLICATION TO FLEXIBLE PAVEMENT SYSTEM

In summary, study of critical HMAC thickness (Problem 1) and critical stress along HMAC surface layer (Problem2) concludes that:

1. A high value of the E_1/E_2 ratio is discouraged;
2. If a high value of E_1/E_2 cannot be avoided, then the HMAC thickness of 1 inch to 6 inches should be avoided; and;
3. High values of E_1/E_2 result in tension at the bottom of the surface layer when the HMAC is very thin, while low values result in compression.

For application to FPS-11 (1), which is currently in use in Texas, when E_1/E_2 is high, there are two design alternatives:

1. Set $D_1 \geq 6$ inches for initial construction, or
2. Set $D_1 = 1$ inch for initial construction and more than 5 inches for the first overlay construction in addition to level up.

Study of the softening of base material (Problem 3) shows that the tensile stress at the bottom of the top layer under the load increases rapidly when the elastic modulus of the upper 0.5 inches of the base course decreases below 25,000 psi. As the upper 0.5 inches of the base course becomes wetter as a result of infiltration or vapor condensation, then the elastic modulus of the base course will decrease and result in higher tensile stresses at the bottom of the top layer. This will accelerate fatigue deterioration of the pavement. If this condition is expected to occur during the life of the pavement, then it is suggested that the FPS-stiffness coefficient for the base course be reduced to take into account the expected reduction in pavement service life. More field and laboratory information is needed to determine to what extent the stiffness coefficient should be reduced when this condition occurs.

REFERENCES

1. "Texas Highway Department Pavement Design System, Part 1 - Flexible Pavement Designer's Manual," Texas Highway Department, 1972.

2. D.Y. Lu, C.S. Shih and F.H. Scrivner, "The Optimization of a Flexible Pavement System Using Linear Elasticity," Research Report 123-17, Texas Transportation Institute, 1973.