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16. Abstract

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4. Regression of Texas Triaxial Model Based on Fibonacci Search,
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THE OPTIMIZATION OF A FLEXIBLE PAVEMENT SYSTEM USING LINEAR ELASTICITY

by

Danny Y. Lu
Chia Shun Shih
Frank H. Scrivner

Research Report Number 123-17

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

March 1973

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PREFACE

This is the seventeenth of a series of reports issued under Research Study 1-8-69-123, "A Systems Analysis of Pavement Design and Research Implementation." This study 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.

Included herein is the description of the studies concerning the integration of the Flexible Pavement System (FPS) computer program and BISTRO*, and elastic layered system program. Special emphases have been placed upon the economization of computation processes, and the evaluation of the structural feasibility of materials.

Special appreciation is extended to Mr. James L. Brown of the Texas Highway Department for technical advice and consultation in the area of pavement systems analysis. Also, special thanks must be addressed to Drs. R. L. Lytton and R. M. Olson for their constructive comments and suggestions.

The cooperation and assistance given by many individuals in both the Texas Highway Department and the Texas Transportation Institute are also sincerely appreciated. Dr. W. M. Moore and Mr. D. L. Schafer of TTI were particularly helpful through this research effort.

* by Koninklijkel Shell Laboratorium, Amsterdam.

March 1973

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.

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.

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 clay parameter used in pavement design system.

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

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.

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 W. M. Moore, describes a computer program which will serve as a subsystem of a future Flexible Pavement System founded on linear elastic theory.

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.

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.

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.

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.

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.

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 FPS-9.

Report No. 123-12, "A Pavement Feedback Data System," by Oren G. Strom, W. Ronald Hudson, and James L. Brown, defines a data system to acquire, store, and analyze performance feedback data from in-service flexible pavements.

Report No. 123-13, "Benefit Analysis for Pavement Design System," by W. 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.

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

Report No. 123-16, "Fatigue and Stress Analysis Concepts for Modifying the Rigid Pavement Design System," by Piti Yimprasert and B. Frank McCullough, presents the development of a mathematical model for simulating the behavior of rigid pavement under repeated loads.

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 on evaluation of structural feasibility of materials.

ABSTRACT

This report integrates linear elastic theory into the current version of the Texas Flexible Pavement Design System in order to give an objective analysis base for the structure feasibility determination based on the internal stresses and surface deflections caused by a dual-wheel load of 9,000-lb.

Included in the report are:

1. Layered Pavement Structure Under Dual-Wheel Load,
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5. Means for Checking the Structure Feasibility of Materials,
6. Two Examples of the Use of FPS-BISTRO.

KEY WORDS: basic design, BISTRO, computer program, dual-wheel load, Fibonacci search, flexible pavement system, multi-dimension spline interpolation, optimization, pavement structure, spline function, strains, stresses, structure feasibility, system analysis, Texas Triaxial compression test, trial design.

SUMMARY

The Texas Flexible Pavement Design System (FPS) has integrated the concepts of the serviceability index, pavement deflections, traffic projections, and swelling clay effects, as well as the costs information pertaining to initial construction, routine maintenance, surface rehabilitation, and user's contribution, into a broad based optimization procedure. In FPS the estimation of structural feasibility is based on the growth of surface deterioration which, in turn, depends on the magnitude of the "surface curvature index" (SCI) computed from experimental and historical relationships. It is known, however, that in some cases pavement life predictions based solely on the SCI are obviously in error: what appears to be needed at this time is a means for screening all trial designs by comparing computed stress with measured material strength, and rejecting designs that are too weak.

Linear Elasticity has been widely applied to the description of the structural behavior of engineering materials. Many versions of programming routines have also been developed for the analysis of layered flexible pavement structures.

It is thus envisioned that the application of Linear Elastic Theory for computing stresses may facilitate an objective analysis for the evaluation of surface behavior. BISTRO is a computer program package developed for determining stresses, strains and displacements in an ideally elastic multi-layer road system. With the integration of FPS and BISTRO, stress-strength comparisons are included in the economic optimization for Flexible Pavement Design and Maintenance. In order to economize the computation process, the original BISTRO has been revised and a multi-dimension spline interpolation routine has been developed.

Strengths (both tensile and compressive) are estimated from the Texas Triaxial Compressive Test because of the long and extensive use of this test by the Texas Highway Department to establish comparative strengths of flexible pavement base, subbase, and subgrade materials.

Two numerical examples are presented herein for the illustration of the application of this FPS-BISTRO System.

IMPLEMENTATION STATEMENT

Detailed instructions for the utilization and application of the FPS-BISTRO System will be presented in a seperate report. Three important features concerning the application of the System deserves special emphasis here: (1) further refinements of the methodology concerning material strength determinations must be accomplished before this system can be implemented with full confidence; (2) the results of the use of BISTRO (i.e. stresses, strains and surface deflections) must be stored and documented to form the basic building blocks of the structure characteristics bank for future implementation and analysis, and (3) the performance equations need to be refined in order to enhance the effectiveness of the FPS-BISTRO System in practical applications.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Basic Philosophy of This Study: Systems approach to the structural design of highway pavements has been viewed as a challenging and intriguing task to applied researchers since the late 1960's (1), (2). The complexity of highway pavement systems is fully recognized because of the interactive characteristics of many design variables, that include those defining the loads, the pavement structure, the construction, the maintenance, the materials, the environment, the performance, and the economics. Though subjective decision making may play an important role in the eventual selection of a final design, the objective analysis imbedded in the systems approach may offer a full range of unbiased identification of alternative courses of action for optimum design considerations.

Thus, pavement behavior and its socio-economic consequences, are such complicated phenomena that they cannot be completely described by a single mathematical equation or model. Instead, a total coordinated and systematic approach based on the coupling of different subsystems defined for specific physical, social, and economical considerations can integrate all the fundamental relationships into a systems optimization procedure.

In mathematical modeling, the routine of model development normally includes the following two cyclic processes: (1) the cycle between the confrontation of the data and the elaboration of the model, and (2) the cycle between the search for tractability and the complexity of the model formulation. The optimization procedures developed for the highway pavement systems have been undergoing the above two cyclic processes simultaneously since the beginning of this project.

The initial version of the systems approach to flexible pavement design integrated the concepts of the serviceability index, pavement deflections, traffic projections, swelling clay effects, initial construction costs, maintenance costs, seal coat costs, overlay costs, and highway user's costs, into a broad based optimization procedure. Since then, different refinements and modifications have been added to the initial version: for instance, the inclusion of a more rational method of using swelling clay parameters in the projection of the serviceability index, the addition of the design confidence level, etc.

However, the determination of the feasibility of a trial design based solely on its estimated tolerance of surface deflections, is completely dependent, in the current approach, on empirical relationships derived from experimental and historical data. It is envisioned that the application of linear elastic theory may provide a means for the identification of the feasibility of each trial design based not only on deflections at the surface but also on <u>stresses within the structure</u>. While elastic theory must be regarded only as a first approximation to the true stress distribution in granular materials, the need to study its practicality and adaptability in this kind of application led directly to the studies described in this report.

1.2 <u>Objective and Scope of This Study</u>: The objective of this study is to integrate linear elastic theory into the current version of the Texas Highway Department's flexible pavement optimization procedures, in order to provide additional information for use in identification of the feasibility of each trial design and overlay policy.

The scope of this study includes the following basic tasks:

(1) To revise the BISTRO program developed by the Shell Oil Company in Holland into an efficient subroutine.

(2) To integrate the revised BISTRO program into the current version of the flexible pavement design system (FPS).

(3) To develop a multi-dimensional interpolation routine for the application of the revised BISTRO program to the analysis of structure and surface response due to a dual-wheel load.

(4) To develop a method for the estimation of limiting tensile and compressive strengths of common flexible pavement materials from standard Texas triaxial compression test data (10).

With respect to the specific tasks mentioned above, the remaining chapters in this report will cover the following:

Chapter 2 - Layered Pavement Structure

Chapter 3 - Analysis of Linear Elasticity by BISTRO

Chapter 4 - Integration of FPS and BISTRO

Chapter 5 - Use of Texas Triaxial Test Data

Chapter 6 - Two Illustrative Examples

Chapter 7 - Conclusions and Recommendations

CHAPTER 2

LAYERED PAVEMENT STRUCTURE

In this report, a flexible highway pavement is regarded as a multi-layer elastic structure with asphaltic concrete as its top layer. Linear elastic theory is used in calculating certain surface deflections, as well as the stresses and strains at selected points within the structure. Computed stresses due to a 9,000-lb. dual-wheel load, are used as one check of the feasibility of the dimensions in trial designs. Computed vertical surface displacements are used to predict the economic life, a second check of feasibility based on the pavement performance equation developed by Scrivner and Michalak (3). This chapter will describe the structural design variables, the dual-wheel load, the "surface curvature index," and the selected points within the structure for the analysis of stresses and strains.

2.1 Structural Design Variables: There are three classes of structural design variables considered herein for a flexible pavement system: (1) number of layers, (2) material constants for each layer, and (3) thickness of each layer. The sketch in Figure 1 represents a pavement cross-section composed of n layers of different materials including the subgrade. The first (top) layer is always asphaltic concrete, and the $n\text{th}$ 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. The thickness of the $i\text{th}$ layer is represented by D_i. The subgrade material is considered to be of infinite thickness.

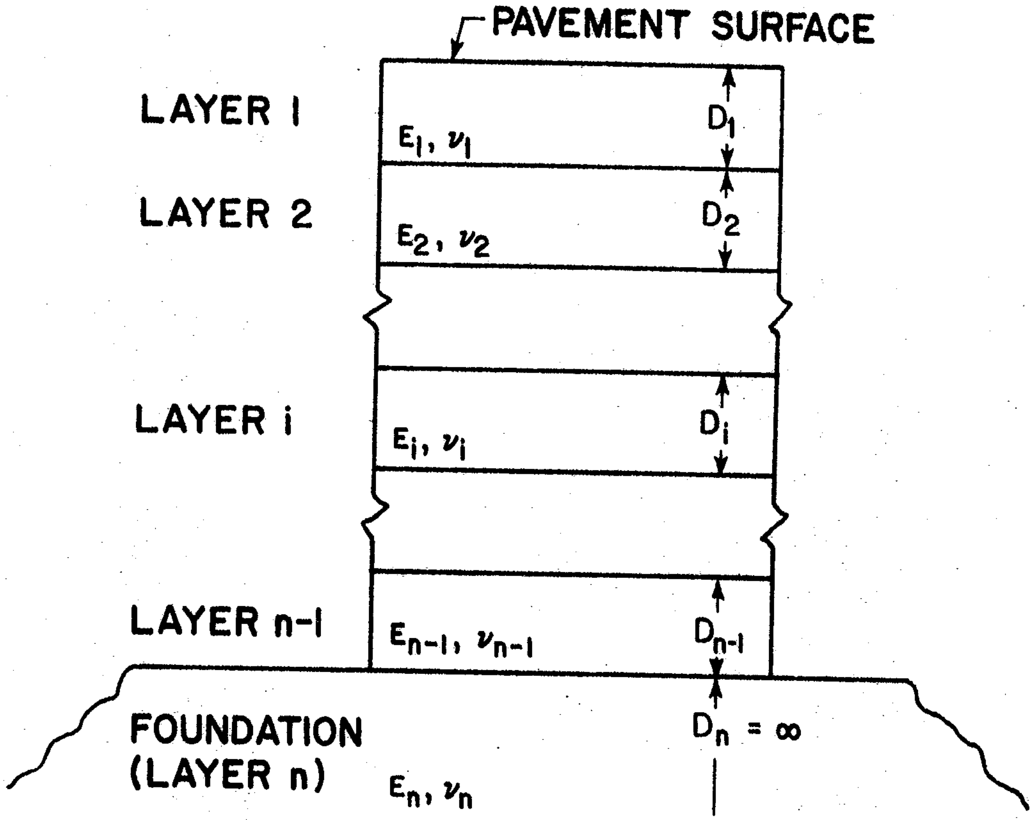


Figure 1: A pavement section of n layers.

2.2 Dual-Wheel Load: Major factors affecting the serviceability of the layered pavement structure are the magnitude and frequency of load application. To evaluate the loss of serviceability, the load spectrum is normalized to an equivalent number of 18,000-lb. single axle loads. Each such axle load is assumed to be applied to the pavement surface through four tires. Figure 2 shows the dual-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.

2.3 Surface Curvature Index: Figure 3, with the vertical scale greatly exagerated, shows a typical deflection basin resulting from a dual-wheel load. The "surface curvature index", the parameter used to predict the ageing effect of a pavement surface, defines the surface deflection basin near the load. The value of the "surface curvature index", S, is computed by Eq. 2.1,

$$S = \frac{W_A - W_B}{20} \times 1000 \qquad (2.1)$$

where W_A is the deflection in inches occuring at Point A, and W_B represents the deflection at Point B. Values of W_A and W_B under the dual-wheel load for a proposed design are computed based on linear elastic theory. In general, the length of economic life of a pavement surface is assumed to be inversely related to the value of the "surface curvature index". Hence, the "surface curvature index" is included in the performance equation to project the loss of serviceability of a specific pavement (3).

2.4 Principal Stresses and Strains: In a layered pavement, the critical stresses and strains usually occur either just above or just below the

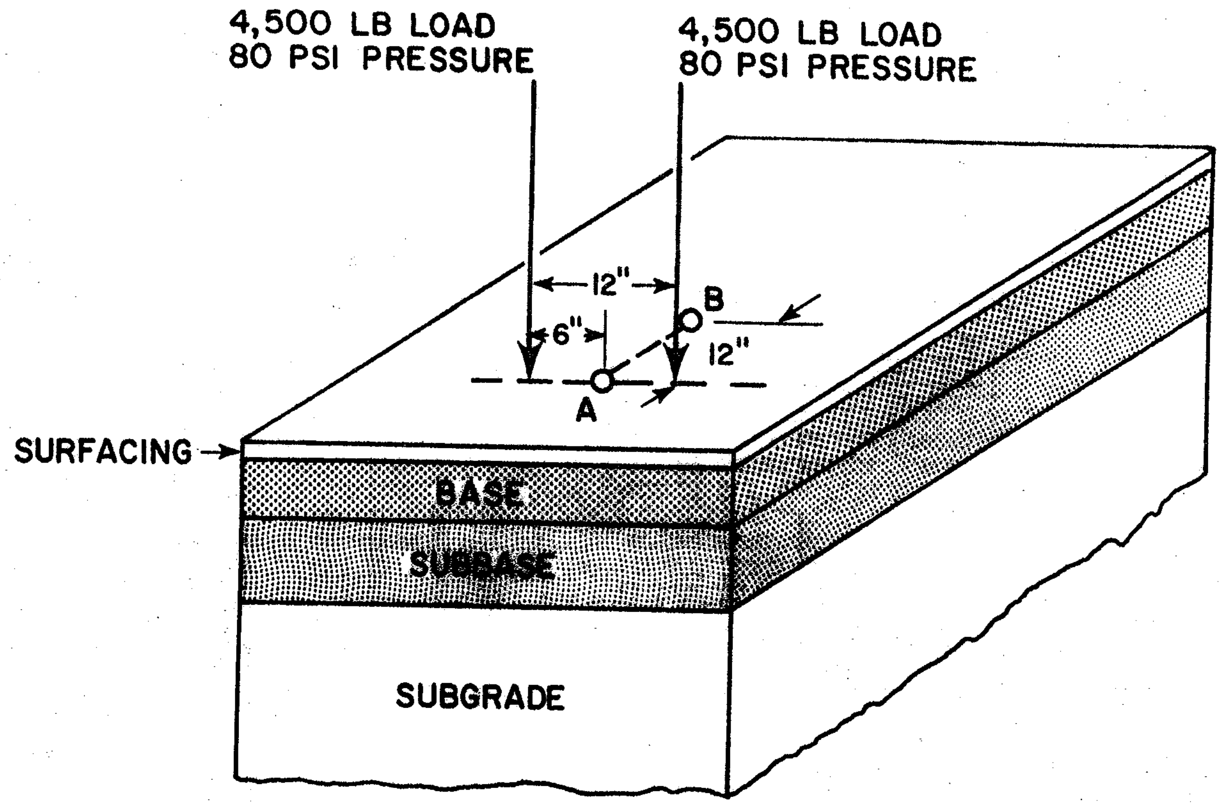


Figure 2: Dual-wheel load of one end of an 18-kip axle.

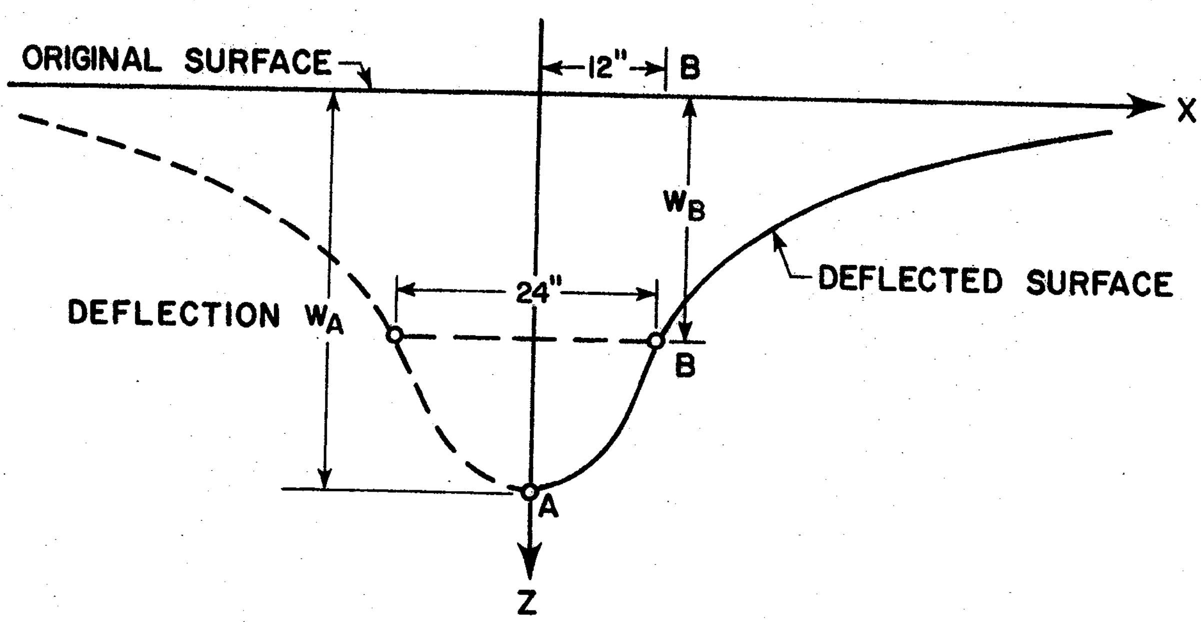


Figure 3: Typical deflection basin of the dual-wheel load as it would appear on a vertical plane through the points A and B.

interfaces. It was assumed that the principal stresses directly under the center of either load at layer interfaces were the critical stresses to be compared with material strength. Figure 4 shows 4(n-1) interfacial points of a n layer design under the dual-wheel load. Because of symmetry, only 2(n-1) points are considered. Major and minor principal stresses and strains at 2(n-1) interfacial points are computed based on linear elastic theory. These stresses are compared with Texas triaxial test results as a feasibility check. Checks for strains are left for future research, inasmuch as limiting values of strains for pavement and subgrade materials are not readily available while values of limiting stress can be estimated from the standard Texas triaxial test.

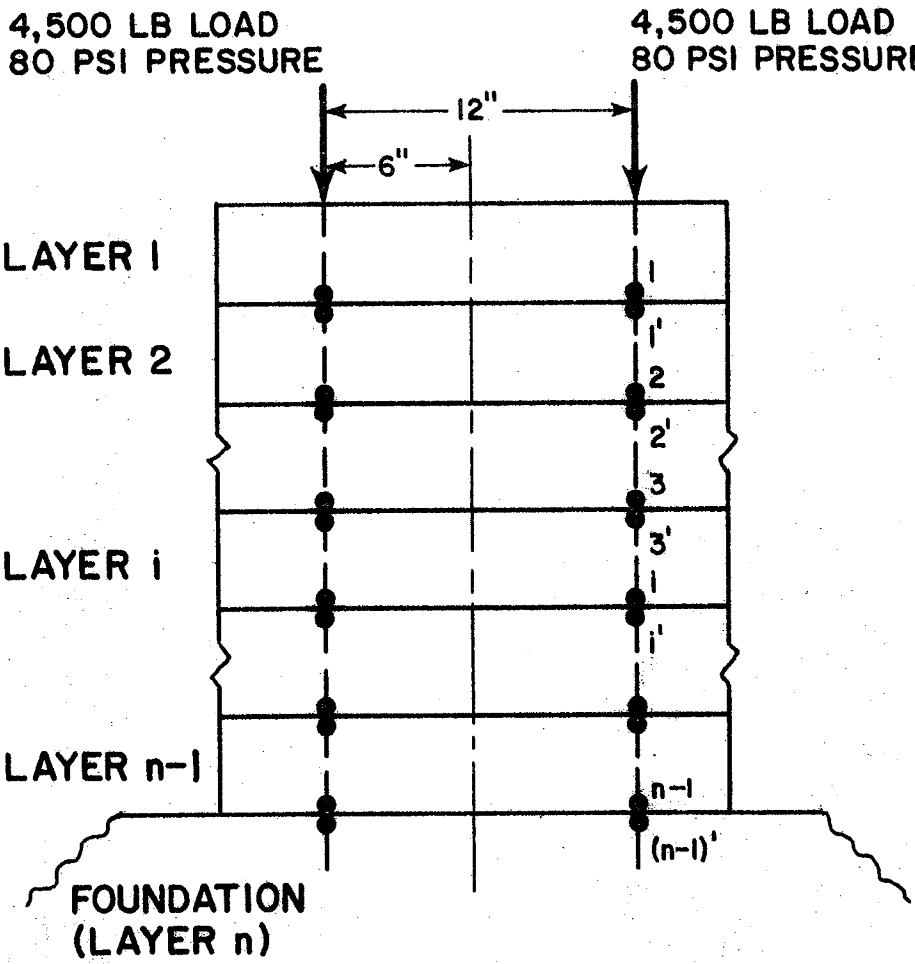


Figure 4: Interfacial points under dual-wheel load.

CHAPTER 3

ANALYSIS OF LINEAR ELASTICITY BY BISTRO

Current methods of highway pavement design rely heavily on empirical rules. However, a number of researchers have investigated the feasibility of the application of linear elasticity to predict the stresses, strains, and surface deformations in pavement structures (4). This chapter describes one approach to the application of linear elasticity to pavement design.

Some researchers have felt that the application of elastic theory is severely limited by the unacceptable amount of computation time required. Thus, the reduction of computation time has been the basic consideration in the development of the application approach.

3.1 Original BISTRO Program: The computer program, BISTRO, was developed for the numerical computation of stresses, strains, and displacements at any position under the road surface. The program has the built-in options for one or more vertical surface loads applied uniformly over circular areas. The input data required are as follows:

(1) number of layers, together with the elastic modulus, Poisson's ratio and thickness of each layer;

(2) number of loaded areas, together with the applied unit pressure, the radius, and the coordinates of the center, of each;

(3) request-options for outputs desired; and

(4) number of desired positions in the structure where computations are to be made, as well as the layer number and coordinates of each position.

The program BISTRO will compute the following items based on the user's options:

(1) vertical, radial, tangential and shear strains and stresses;

(2) vertical and radial displacements;

(3) principal strains and stresses with their orientation; and

(4) principal displacements (parallel to the principal strain directions).

3.2 <u>Revised BISTRO Program</u>: BISTRO is a comprehensive programming package for the analysis of multi-layer, linear elastic structures. Although different versatilities and computational options have been built into the BISTRO system for the user's specifications, the computation time requirement for each original BISTRO run is too much to qualify BISTRO as a practical tool in the flexible pavement system treated herein. It thus became inevitable and indispensable to reduce the computation time requirement of BISTRO for the determination of stresses, strains, and displacements in a finite-layer flexible pavement structure.

The following two types of modifications were made in the BISTRO program in order to reduce its running time significantly: (1) the inclusion of specific changes of programming statements while not affecting the accuracy of the output; and (2) the relaxing of accuracy criteria in determining the zeros of Bessel functions and in performing numerical integrations, again with negligible sacrifice of overall computation accuracy.

The revised BISTRO was further modified into a subroutine of the Texas Flexible Pavement System computer program (FPS). Inputs to this subroutine include: (1) physical characteristics of the pavement structure which consist of the elastic modulus, the Poisson's ratio, and the thickness of each layer, and (2) the desired level of accuracy -- excellent, good, or fair. The surface curvature index, and the major and minor principal stresses and strains at the inter-layer positions indicated in Figure 4, are then calculated.

3.3 Comparison of Original and Revised BISTROs: A comparison in terms of the accuracy and total machine time consumed by the original and three revised versions of BISTRO were made as illustrated in the following example.

A three-layer pavement structure as described in the following table is used for computational comparison:

Layer No.	Material	Elastic Modulus (psi)	Poisson Ratio	Thickness (in.)
1	Asphaltic Concrete	240,000	0.5	1
2	Black Base	150,000	0.5	4
3	Subgrade	24,000	0.5	-

The problem is to find the surface curvature index (SCI), and the major and minor principal stresses and strains at four interfacial positions. Figure 5 shows the four positions and their assigned position numbers. Computer outputs are listed in Table 1. Program A is the original BISTRO. Programs B, C, and D are revised BISTROs with accuracy levels "excellent", "good", and "fair", respectively. Symbols $\sigma_{I,i}$ and $\sigma_{III,i}$ represent major and minor principal stresses at position i. Symbols $\varepsilon_{I,i}$ and $\varepsilon_{III,i}$ represent major and minor principal strains at position i. These programs were run on the IBM 360/65 at the Data Processing Center at Texas A&M University.

It appears that the results from the original BISTRO and the revised BISTRO with "excellent" accuracy level are identical whereas the machine time requirements are in the ratio of 1.72 to 1.17. Meanwhile, the revised BISTRO with "good" accuracy level also gives almost identical values with a few exceptions which only show some differences in the third digit. The resulting numerical difference is no more than 1%. But the machine time requirements are at the ratio of 1.72 to 0.91 between the original BISTRO and

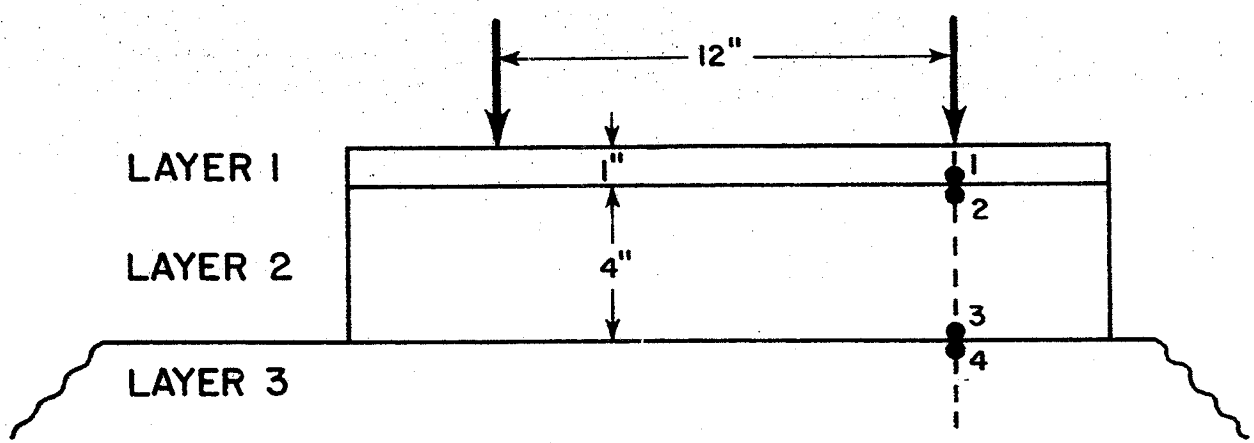


Figure 5: A three-layer pavement structure with four interfacial positions.

TABLE I: Comparison of output of the original and three modifications of BISTRO

Program	A	B	C	D
Agreement with Original BISTRO	---	Excellent	Good	Fair
Computer execution time (minutes)	1.72	1.17	0.91	0.79
SCI	0.323	0.323	0.323	0.323
$\sigma_{I,1}$	-0.721E 02	-0.721E 02	-0.721E 02	-0.719E 02
$\sigma_{III,1}$	-0.781E 02	-0.781E 02	-0.781E 02	-0.782E 02
$\sigma_{I,2}$	-0.728E 02	-0.728E 02	-0.729E 02	-0.726E 02
$\sigma_{III,2}$	-0.778E 02	-0.778E 02	-0.778E 02	-0.782E 02
$\sigma_{I,3}$	0.854E 02	0.854E 02	0.854E 02	0.854E 02
$\sigma_{III,3}$	-0.252E 02	-0.252E 02	-0.252E 02	-0.252E 02
$\sigma_{I,4}$	-0.747E 01	-0.747E 01	-0.747E 01	-0.747E 01
$\sigma_{III,4}$	-0.253E 02	-0.253E 02	-0.253E 02	-0.253E 02
$\varepsilon_{I,1}$	0.239E-04	0.239E-04	0.237E-04	0.256E-04
$\varepsilon_{III,1}$	-0.137E-04	-0.137E-04	-0.137E-04	-0.138E-04
$\varepsilon_{I,2}$	0.317E-04	0.317E-04	0.313E-04	0.346E-04
$\varepsilon_{III,2}$	-0.179E-04	-0.179E-04	-0.176E-04	-0.212E-04
$\varepsilon_{I,3}$	0.417E-03	0.417E-03	0.417E-03	0.417E-03
$\varepsilon_{III,3}$	-0.689E-03	-0.689E-03	-0.689E-03	-0.689E-03
$\varepsilon_{I,4}$	0.417E-03	0.417E-03	0.417E-03	0.417E-03
$\varepsilon_{III,4}$	-0.701E-03	-0.701E-03	-0.701E-03	-0.700E-03

the revised BISTRO with "good" accuracy level (Program C). However, the values calculated by Program D (the revised BISTRO with "fair" accuracy level) show significantly greater differences. Thus, it was concluded that the revised BISTRO with "good" accuracy level (Program C) would be the best version, in terms of both running time and numerical accuracy, to be incorporated in the flexible pavement design system.

CHAPTER 4

INTEGRATION OF FPS AND BISTRO

As this study is aimed at the use of linear elasticity as a subsystem of a flexible pavement design system (FPS), maximum effort was devoted to the integration of the existing FPS program and the BISTRO program. Although the BISTRO running time was reduced by approximately 50 percent, it would still be a very expensive program for direct application in FPS. For instance, it might still take more than 500 minutes computer time on the IBM 360/65, to evaluate 1000 trial designs (the limiting number handled by FPS). The cost of evaluating 1000 trial designs and determining the optimal choice thus would be astronomical. In order to overcome this difficulty, a multi-dimension spline interpolation method was developed to replace the BISTRO analysis for each trial design without sacrifice of desired accuracy.

4.1 Spline Functions and Interpolation: A spline function of degree m is a piecewise polynomial function defined in successive intervals by means of arcs of different polynomials of degree at most m. Successive polynomial arcs are joined toegther as smoothly as can be done. Therefore, any two successive polynomials joined at a node have the same ordinate and the same derivative values of orders 1, 2, ... , m-1.

One dimension spline interpolation was developed by Greville (5). Consider the problem of interpolating between n given data points,

(x_i, y_i), $i = 1, 2, \ldots, n$,

where $b \leq x_1 < x_2 < \cdots < x_n \leq d$

x_i = argument value of the i^{th} data point

y_i = function value of x_i

b = lower bound of x_i values

d = upper bound of x_i values

A spline function of an odd order m is defined as follows ($k = (m-1)/2$):

$$s(x) = \sum_{j=o}^{k} a_j x^j \qquad b \le x \le x_1$$

$$= \sum_{j=o}^{k} a_j x^j + c_1 (x - x_1)^m \qquad x_1 \le x \le x_2$$

$$= \sum_{j=o}^{k} a_j x^j + c_1 (x - x_1)^m + c_2(x - x_2)^m \qquad x_2 \le x \le x_3 \quad (4.1)$$

$$\vdots$$

$$= \sum_{j=o}^{k} a_j x^j + \sum_{j=1}^{n} c_j (x-x_j)^m \qquad x_n \le x \le d$$

The $n + k + 1$ parameters, $a_o, a_1, \ldots, a_k, c_1, c_2, \ldots, c_n$ are determined by solving the following $n + k + 1$ simultaneous equations:

$$\sum_{j=o}^{k} a_j x_i^j + \sum_{j=1}^{i} c_j (x_i - x_j)^m = y_i \qquad i = 1, 2, \ldots, n$$

$$(4.2)$$

$$\sum_{j=1}^{n} c_j x_j^r = 0 \qquad r = 0, 1, 2, \ldots, k$$

Given an argument value x, the function value y can thus be determined by setting $y = s(x)$ in Eq. 4.1. Since the numerical process developed for spline function determination includes only simple arithmatic manipulations, the overall computation time is rather short compared with other interpolation methods. For example, the third order spline interpolation only takes about

50 percent of the computer time required for interpolation by a second order polynomial regression, with similar accuracy.

4.2 Multi-Dimension Spline Interpolation: A special multi-dimension spline interpolation method has been developed by the authors to facilitate the use of BISTRO in FPS. It is essentially a multiple polynomial interpolation. Compared with general multiple and polynomial regression methods, it is most applicable, especially when the required order of a polynomial model is unknown.

This interpolation scheme is conducted over either evenly or unevenly spaced points, called grid points, in a n-dimension euclidean space. Each coordinate is assigned m_i values, $i = 1, 2, \ldots, n$. There are $m_1 \times m_2 \times \ldots \times m_n$ grid points in total. The interpolation for this n-dimension space is performed by interpolating one dimension at a time with the spline routine described in Section 4.1.

A two-dimension sample space, $n = 2$, is used to illustrate the interpolation procedure, as shown in Figure 6. Consider the problem of interpolating between $m_1 \times m_2$ given data points, (x_{ij}, y_{ij}), where x_{ij} and y_{ij} designate the independent and dependent variable values at the sampling point, with the i^{th} value on the horizontal axis and the j^{th} value on the vertical axis, $i = 1, 2, \ldots, m_1$, and $j = 1, 2, \ldots, m_2$. The problem is to find y_{oo} corresponding to a given value $x = x_{oo}$. Procedures are as follows:

(1) $j = 1$

(2) Conduct a one-dimension spline interpolation of third degree by taking:

i) $(x_{1j}, x_{2j}, \ldots, x_{m_1 j})$ as an array of the independent variable;

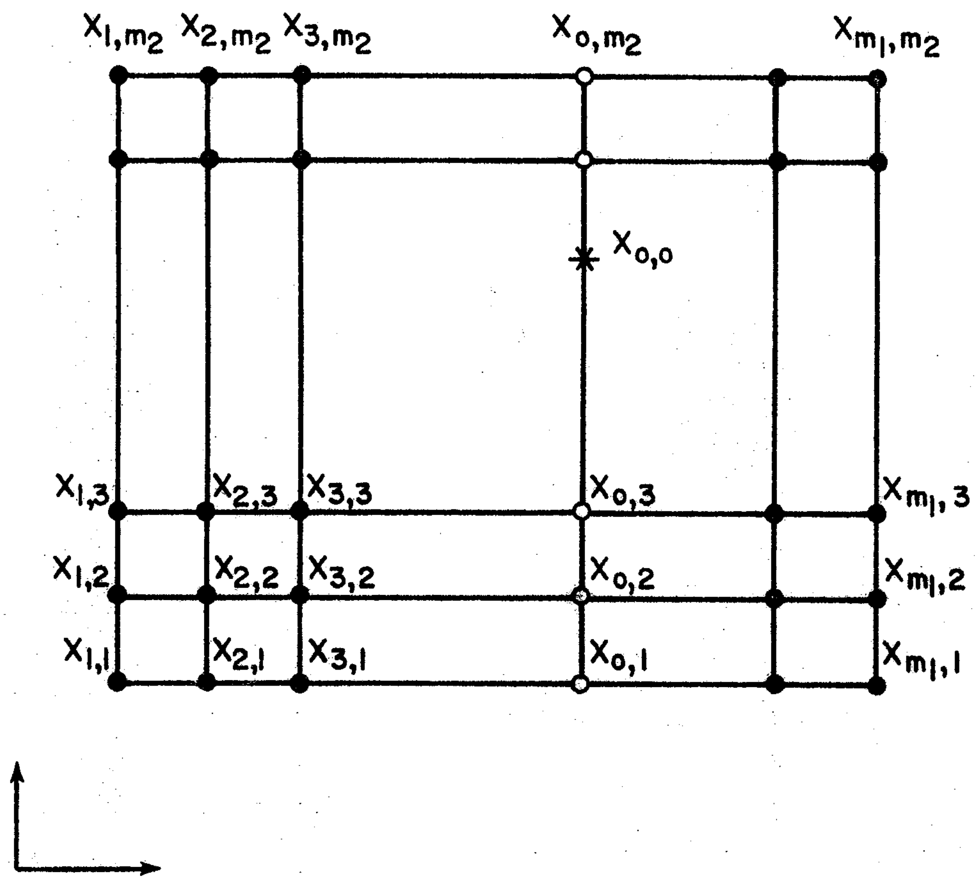


Figure 6: Illustration of a two-dimension spline interpolation.

ii) $(y_{1j}, y_{2j}, \ldots, y_{m_1j})$ as an array of the dependent variable;

iii) x_{oj} as an argument.

Then y_{oj} is interpolated.

(3) If $j < m_2$, set $j = j + 1$, and go to step (2).

(4) If $j = m_2$, conduct a one-dimension spline interpolation of third degree for the interpolated value by taking:

i) $(x_{o1}, x_{o2}, \ldots, x_{om_2})$ as an array of the independent variable;

ii) $(y_{o1}, y_{o2}, \ldots, y_{om_2})$ as an array of the dependent variable; and

iii) x_{oo} as an argument.

Then y_{oo} is interpolated.

4.3 <u>Interpolation of BISTRO Output</u>: Multi-dimension spline interpolation is used to replace the BISTRO analysis for trial designs.

In a n-layer pavement, 5^{n-1} basic designs with the same material constants are evaluated by the revised BISTRO program to construct an interpolation basis (or frame work). Any other n-layer design, with the same material constants, but a different thickness combination, can thus be interpolated. Estimated computer execution times to calculate the surface curvature index, and major and minor principal stresses and strains at 2(n-1) positions, on the IBM 360/65, are shown in Table 2.

Table 2: Estimated computer execution time to evaluate basic designs by BISTRO with excellent accuracy level.

No. of Layers	No. of Basic Designs	Estimated Computer Time (min.)
2	5	5
3	25	20
4	125	80
5	625	320

In order to avoid unnecessary computer costs, only a three-layer design is actually programmed and tested in this study.

In a three-layer pavement structure, for different thicknesses of both first and second layers, spacings within the prescribed range are used to form basic designs. The uneven spacing of grid points within the range of thickness of the first layer (asphaltic concrete layer) was found from experience to be necessary to achieve better accuracy of interpolation as shown in Figure 7.

The interpolation of a three-layer pavement design system is discussed below and illustrated in Figure 7. Symbols used in Figure 7 are as follows:

D_1 = thickness of the first layer

D_2 = thickness of the second layer

D_{11} = minimum allowed thickness of the first layer of the initial design

D_{15} = maximum allowed thickness of the first layer of the initial design, + accumulated maximum allowed depth of all overlays, excluding level up

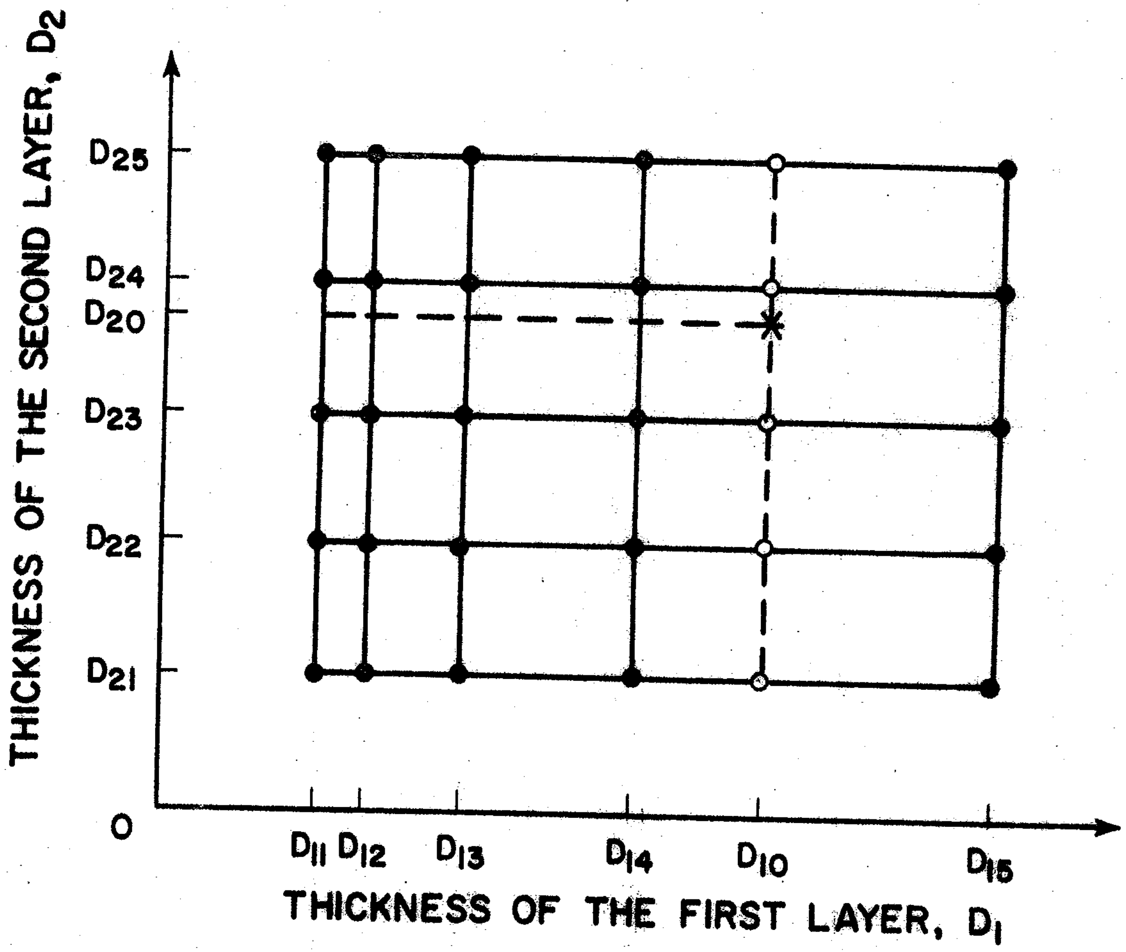


Figure 7: Interpolation of a three-layer design. The point to be interpolated is indicated by the asterisk.

$D_{12} = D_{11} + (D_{15} - D_{11})/15$

$D_{13} = D_{12} + 2(D_{15} - D_{11})/15$

$D_{14} = D_{13} + 4(D_{15} - D_{11})/15$

D_{21} = minimum allowed thickness of the second layer of initial design

D_{25} = maximum allowed thickness of the second layer of initial design

$D_{22} = D_{21} + (D_{25} - D_{21})/4$

$D_{23} = D_{22} + (D_{25} - D_{21})/4$

$D_{24} = D_{23} + (D_{25} - D_{21})/4$

Twenty-five combinations of thickness, (D_{1i}, D_{2j}), i = 1, 2, ... , 5, j = 1, 2, ... , 5, with the same material constants are defined as the required basic designs. Any other three-layer trial design with the same material constants and the thickness combination, (D_{10}, D_{20}), can thus be interpolated by the two-dimension spline interpolation discussed in the preceeding section.

4.4 Accuracy of Interpolation: In order to compare the accuracy of interpolation, an illustrative example is presented. Suppose that the physical characteristics of a proposed three-layer pavement structure is as follows:

Layer No. k	Material	Elastic Modulus (psi)	Poisson Ratio	D_{k1}(in).	D_{k5}(in).
1	Asphaltic Concrete	240,000	0.5	1	16
2	Black Base	150,000	0.5	4	20
3	Subgrade	24,000	0.5	-	--

Twenty-five basic designs are evaluated by the revised BISTRO at first. Two trial designs, A and B, are to be obtained by interpolation. For design A, D_1 = 1.5 inches and D_2 = 6 inches. For design B, D_1 = 12 inches and D_2 = 18 inches. Figure 8 shows twenty-five basic designs to be evaluated by Bistro,

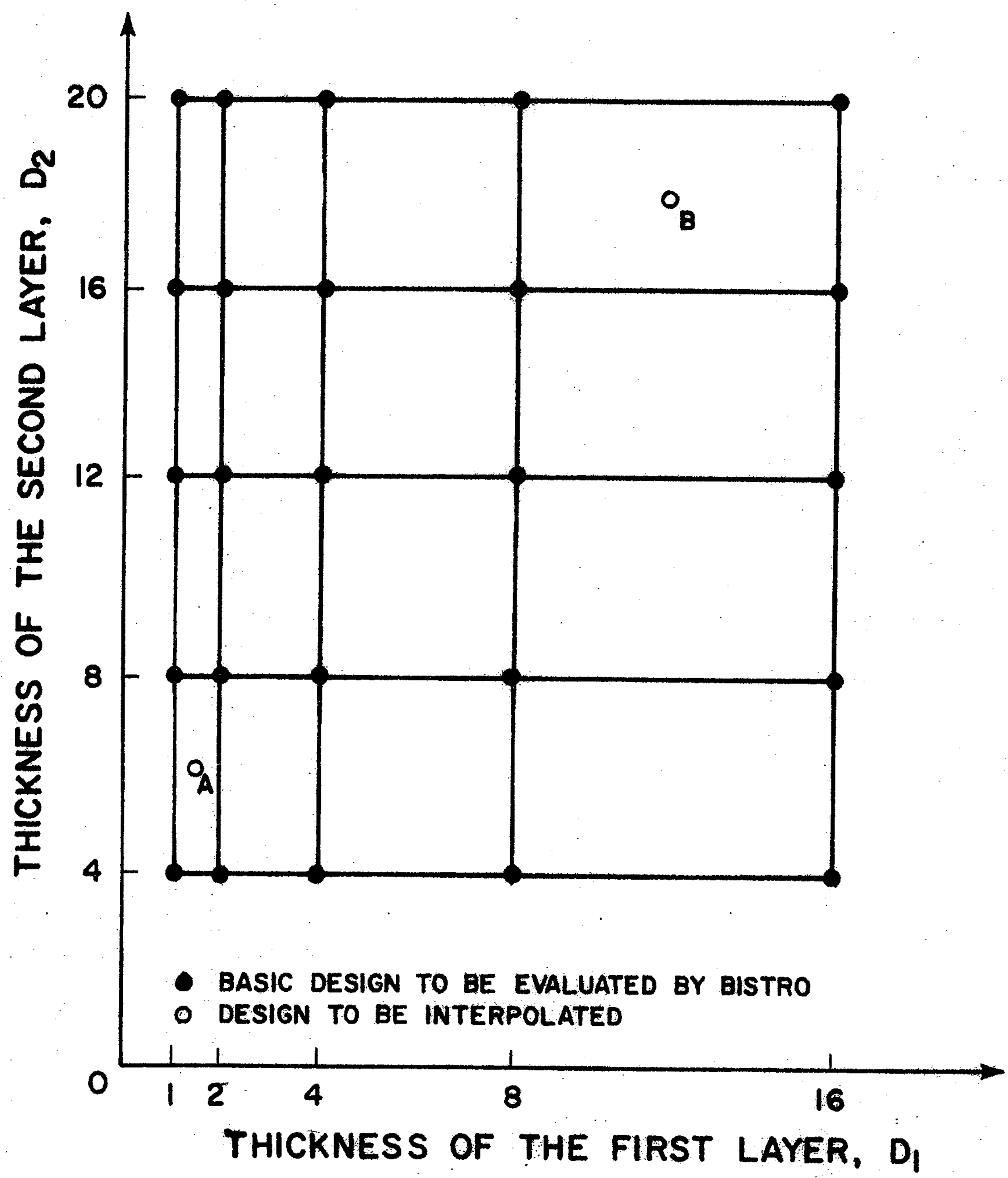


Figure 8: Sampling points of 25 basic designs and 2 trial designs, A and B.

and the two trial designs, A and B, to be interpolated.

Interpolated values are compared with revised BISTRO outputs in Table 3. The accuracy level of "excellent" was used. Symbols SCI, $\sigma_{I,i}$; $\sigma_{III,i}$; $\varepsilon_{I,i}$ and $\varepsilon_{III,i}$ are defined as in Table I. It was observed that the computer execution time was only 2.4 seconds, on the IBM 360/65, for the interpolation of seventeen output values, i.e., 0.14 second per output value.

TABLE 3: Comparison of BISTRO outputs, and Interpolated values.

Design	A		B	
	Revised BISTRO	Interpolation	Revised BISTRO	Interpolation
SCI	0.211	0.221	0.058	0.057
$\sigma_{I,1}$	-0.442E 02	-0.437E 02	0.700E 01	0.673E 01
$\sigma_{III,1}$	-0.754E 02	-0.742E 02	-0.131E 02	-0.132E 02
$\sigma_{I,2}$	-0.555E 02	-0.547E 02	-0.379E 00	-0.579E 00
$\sigma_{III,2}$	-0.756E 02	-0.743E 02	-0.133E 02	-0.134E 02
$\sigma_{I,3}$	0.565E 02	0.583E 02	0.691E 01	0.696E 01
$\sigma_{III,3}$	-0.151E 02	-0.160E 02	-0.161E 01	-0.163E 01
$\sigma_{I,4}$	-0.365E 01	-0.410E 01	-0.243E 00	-0.245E 00
$\sigma_{III,4}$	-0.153E 02	-0.162E 02	-0.163E 01	-0.165E 01
$\varepsilon_{I,1}$	0.670E-04	0.686E-04	0.474E-04	0.477E-04
$\varepsilon_{III,1}$	-0.128E-03	-0.123E-03	-0.781E-04	-0.773E-04
$\varepsilon_{I,2}$	0.702E-04	0.709E-04	0.474E-04	0.477E-04
$\varepsilon_{III,2}$	-0.131E-03	-0.126E-03	-0.817E-04	-0.812E-04
$\varepsilon_{I,3}$	0.272E-03	0.282E-03	0.297E-04	0.299E-04
$\varepsilon_{III,3}$	-0.444E-03	-0.462E-03	-0.554E-04	-0.557E-04
$\varepsilon_{I,4}$	0.272E-03	0.282E-03	0.297E-04	0.299E-04
$\varepsilon_{III,4}$	-0.459E-03	-0.476E-03	-0.570E-04	-0.575E-04
Execution Time	1.09 min.	2.4 sec.	0.67 min.	2.4 sec.

CHAPTER 5

USE OF TEXAS TRIAXIAL TEST DATA

This chapter develops a method for determining non-linear "regression coefficients" using a Fibonacci search. The procedure estimates the lateral tensile strength and a dimensionless parameter from Texas triaxial test data. The estimated values are used in the Texas flexible pavement design system to compare material strengths with the major and minor principal stresses induced in a trial design by the load previously described (Section 2.2).

The writers acknowledge that estimating the tensile strength of a granular material from a compression test is risky, but for the present there is no practical alternative.

5.1 <u>Regression Model</u>: The assumed relationship between vertical and radial failure stresses observed in a Texas triaxial test is given below. In this model, compressive stresses are positive.

$$\sigma_z = U\left[1 + \frac{\sigma_r}{T}\right]^C \qquad (5.1)$$

Where

σ_z = vertical normal stress at failure,

σ_r = radial normal stress, or confining pressure,

U = unconfined compressive strength, $U > 0$,

T = lateral tensile strength with $\sigma_z = 0$, $T > 0$,

C = dimensionless parameter, $0 < C \leq 1$.

The upper limit of C was set to 1.0, because for $C > 1$, unrealistically high values of T would be obtained as a result of the σ_z vs σ_r curve being convex in shape. Eq. 5.1 satisfies two specific conditions:

(i) if $\sigma_r = 0$, then $\sigma_z = U$

(ii) if $\sigma_r = -T$, then $\sigma_z = 0$

This is shown schematically in Figure 9.

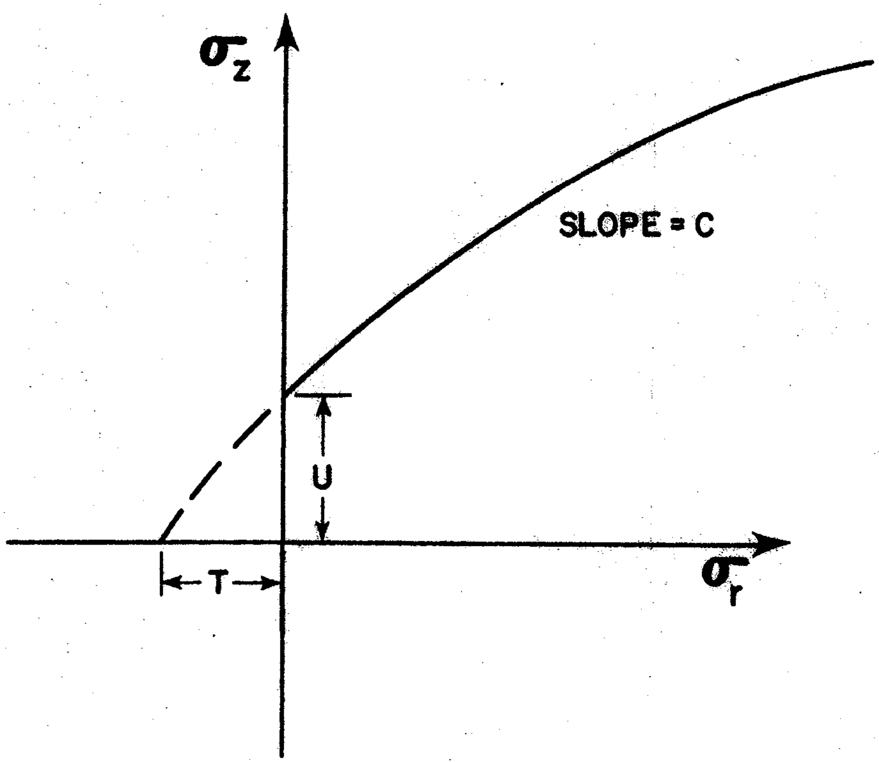


Figure 9: Example of relationship between σ_z and σ_r in a Texas triaxial test.

N + 1 data points, $(\sigma_{ri}, \sigma_{zi})$, i = 0, 1, 2, ... , N, are normally obtained from each Texas triaxial test. By taking $\sigma_{ro} = 0$, the corresponding σ_{zo} is the unconfined compressive strength, U. The remaining N data points, with $\sigma_{ri} > 0$, i = 1, 2, ... , N, are submitted to regression analysis using the following model derived from Eq. 5.1

$$\ln \sigma_z = \ln U + C \ln \left(1 + \frac{\sigma_r}{T}\right) \tag{5.2}$$

where

U is a given constant;

σ_r is an independent variable;

σ_z is a dependent variable; and

C and T are coefficients to be estimated.

The regression method developed in this report is a least squares method using a Fibonacci search.

5.2 <u>Regression Method</u>: A general method to estimate unknown coefficients is the least squares regression. The key point of least squares is to minimize the sum of squares of the prediction errors, i.e.,

$$\text{Min } F(C,T) = \sum_{i=1}^{N} \left[\ln \sigma_{zi} - \ln U - C \ln \left(1 + \frac{\sigma_{ri}}{T}\right)\right]^2 \tag{5.3}$$

C and T can be determined by differentiating Eq. 5.3 first with respect to C and then with respect to T and setting the results equal to zeroes. Now

$$g_1(C,T) = \frac{\partial F}{\partial C} = -2 \sum_{i=1}^{N} \left[\ln \sigma_{zi} - \ln U - C \ln \left(1 + \frac{\sigma_{ri}}{T}\right)\right]\left[\ln\left(1 + \frac{\sigma_{ri}}{T}\right)\right] = 0$$

$$g_2(C,T) = \frac{\partial F}{\partial T} = 2 \sum_{i=1}^{N} \left[\ln \sigma_{zi} - \ln U - C \ln \left(1 + \frac{\sigma_{ri}}{T}\right)\right]\left[\frac{c}{1+\frac{\sigma_{ri}}{T}} \cdot \frac{\sigma_{ri}}{T^2}\right] = 0$$

(5.4)

so that the estimated C and T are solved by a Newton search,

$$\begin{pmatrix} C^{k+1} \\ T^{k+1} \end{pmatrix} = \begin{pmatrix} C^{k} \\ T^{k} \end{pmatrix} - \begin{pmatrix} a_{11}(C^k, T^k) & a_{12}(C^k, T^k) \\ a_{21}(C^k, T^k) & a_{22}(C^k, T^k) \end{pmatrix}^{-1} \begin{pmatrix} g_1 (C^k, T^k) \\ g_2 (C^k, T^k) \end{pmatrix} \tag{5.5}$$

where the superscript k is an interation number, and

$$a_{11}(C,T) = \frac{\partial g_1(C,T)}{\partial C}, \quad a_{12}(C,T) = \frac{\partial g_1(C,T)}{\partial T}$$

$$a_{21}(C,T) = \frac{\partial g_2(C,T)}{\partial C}, \quad a_{22}(C,T) = \frac{\partial g_2(C,T)}{\partial T}$$

Poor convergence was observed when Eq. 5.5 was iterated, so that there existed a need to develop a regression method without taking derivatives. A method using a Fibonacci search was found very efficient to estimate T and C values. Instead of minimizing the sum of squares of prediction errors, this method minimizes the standard error, i.e.,

$$\text{S.E.} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [\ln \sigma_{zi} - \ln U - C \ln(1 + \frac{\sigma_{ri}}{T})]^2} \tag{5.6}$$

Actually, minimizing the standard error is essentially the same as minimizing the prediction errors, because N is a constant, and the square root of a nonnegative term is still nonnegative.

There are two unknowns in Eq. 5.6. In order to conduct a Fibonacci line search, C is approximated by a function of T,

$$C = \frac{\sum_{i=1}^{N} \ln \sigma_{zi} - N \ln U}{\sum_{i=1}^{N} \ln (1 + \frac{\sigma_{ri}}{T})} . \tag{5.7}$$

Substitute Eq. 5.7 into Eq. 5.6; S.E. is then a function with only one variable, T.

A Fibonacci search (6) determines the smallest interval, in which the optimum of a unimodal function lies, after a given number of iterations are completed. In applying a Fibonacci search to the triaxial test model, (Eq. 5.1.), some modifications are made. Instead of determining the smallest interval in which the optimal point lies, the modified method determines the optimal point. This is done by fixing the smallest interval equal to 0.1. The number of Fibonacci interations, NFIB, is then determined by a predicted maximum T value, Tmax. This is shown in Table 4.

Figure 10 shows a flow chart of the solution procedure. After a T value is generated from the Fibonacci search routine, C and S.E. values are calculated from Eq. 5.7 and Eq. 5.6. A next T value is generated again from the Fibonacci search routine. After NFIB Iterations are completed, the smallest S.E.* and corresponding C* and T* values are selected. If C* $\leq$ 1, then C* and T* are taken as the estimated coefficients of the regression model. If C* > 1, then let C* = 1. T* and the standard error of T*, S.E.*, are calculated from Eq. 5.8 and Eq. 5.9.

$$T^* = \frac{U \sum_{i=1}^{N} \sigma_{ri}}{\sum_{i=1}^{N} \sigma_{zi} - NU} \tag{5.8}$$

$$S.E.^* = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [\sigma_{zi} - U(1+\frac{\sigma_{ri}}{T})]^2} \tag{5.9}$$

A computer program, TRIAXIAL, has been written for the numerical computations. Documentation of the computer program is shown in Appendix A. Two

Table 4: Determining the number of Fibonacci iterations, NFIB, by a predicted maximum T value, Tmax*, of Triaxial data.

NFIB	Tmax	NFIB	Tmax
1	0.1	11	14.4
2	0.2	12	23.3
3	0.3	13	37.7
4	0.5	14	61.0
5	0.8	15	98.7
6	1.3	16	159.7
7	2.1	17	258.4
8	3.4	18	418.1
9	5.5	19	676.5
10	8.9	20	1094.6

* Tmax for any given number of iterations, NFIB, is the corresponding Fibonaccian number divided by 10. This limits Tmax to a minimum value of 0.1 psi. Note that each Tmax is the sum of the two preceeding values.

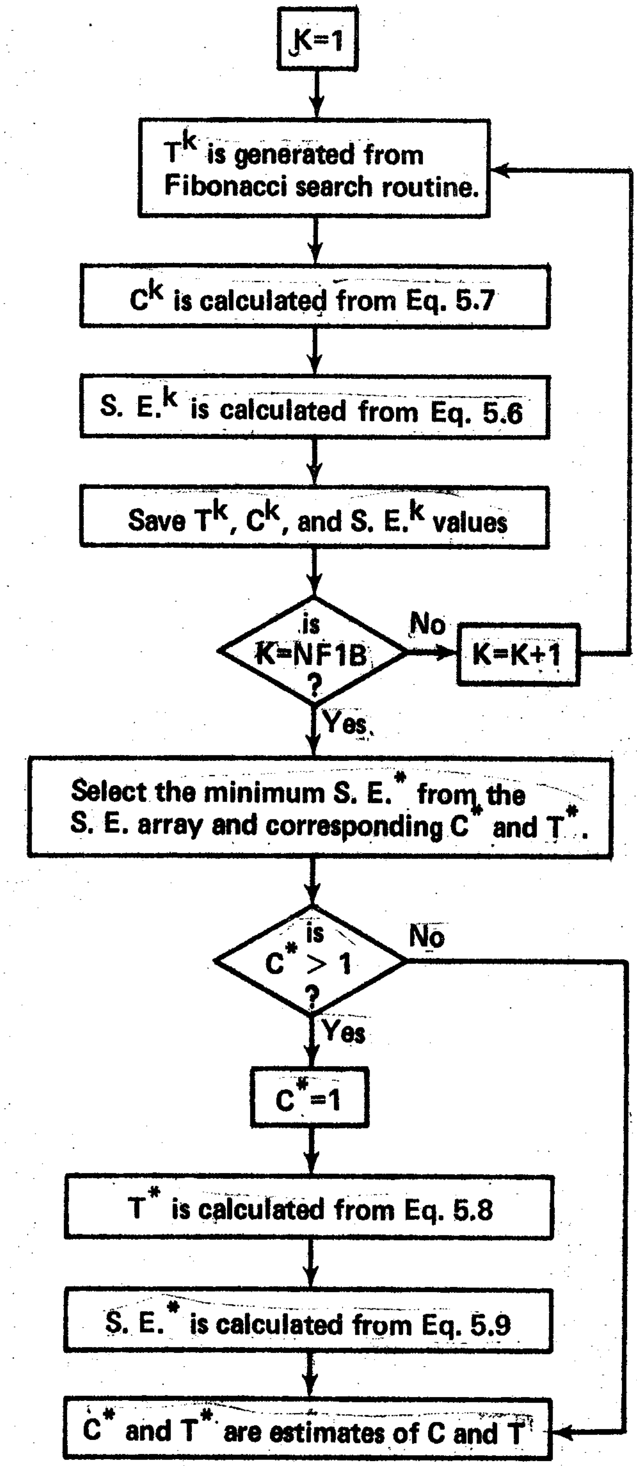


Figure 10: Solution procedure of a least square regression using Fibonacci search to estimate C and T of Triaxial test data.

hundred seventy three example problems have been solved. Inputs and outputs of these examples are listed in Appendices A.3 and A.4 respectively, while plots of six typical problems are shown in this section (Figure 11). (The test results shown on page 36 are for lime stabilized materials and probably are not representative of field conditions because of the accelerated curing procedure used in the laboratory).

The TRIAXIAL program took 0.46 minutes computer time on IBM 360/65 to solve the 273 problems. This regression method has been found to be very efficient and the optimal estimates are guaranteed in a finite number of iterations.

Table 5 is a summary of parameters by soil characteristic categories. This table is obtained from the outputs of the 273 example problems shown in Appendix A.4. Code numbers are defined as follows:

Stabilization Code	Kind of Stabilization
1	None
2	Asphalt
3	Lime

Soil Binder Code	Percent Retained on 40M Sieve
1	0 - 24
2	25 - 49
3	50 - 74
4	75 - 100

Pl Code	Range of Plasticity Index
1	52 and above
2	39 - 51
3	26 - 38
4	13 - 25
5	0 - 12

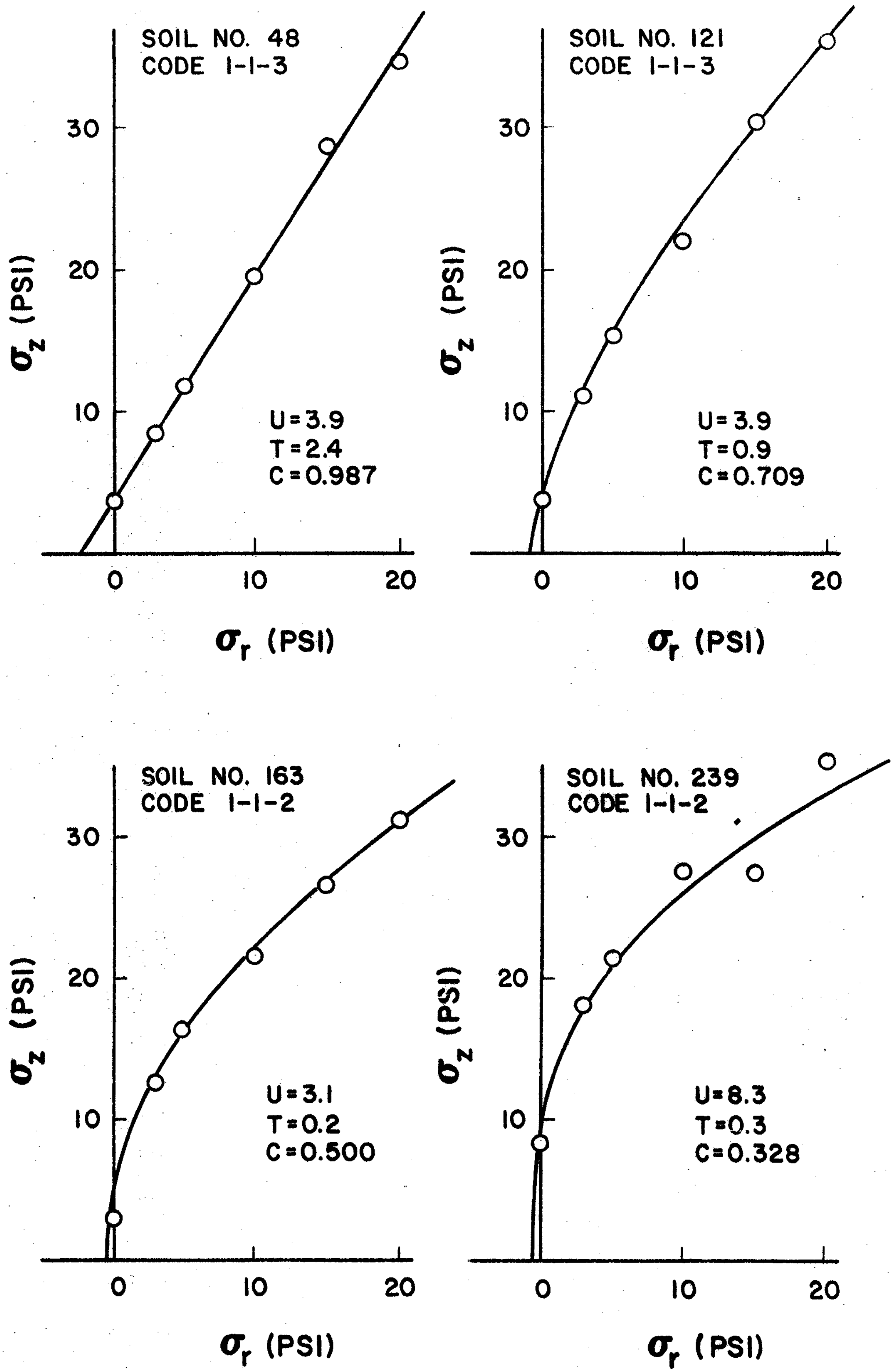
The U, T and C values in Table 5 were regressed on the three codes by a select regression method (7, 8), using a second degree surface as the model. Results are shown in the following equations:

$$U = 6.96 + 9.16\, X_1^2$$

$$(R^2 = 0.744, \text{ Probability of Type 1 Error} = 0.000) \qquad (5.10)$$

$$T = 3.26 - 1.96X_2 - 1.64X_3 + 0.29\, X_3^2 + 1.66X_1X_2$$

$$(R^2 = 0.832, \text{ Probability of Type 1 Error} = 0.094) \qquad (5.11)$$


SOIL NO. 48
CODE 1-1-3
U=3.9
T=2.4
C=0.987
SOIL NO. 121
CODE 1-1-3
U=3.9
T=0.9
C=0.709
SOIL NO. 163
CODE 1-1-2
U=3.1
T=0.2
C=0.500
SOIL NO. 239
CODE 1-1-2
U=8.3
T=0.3
C=0.328
σ_z (PSI)
σ_r (PSI)
0
10
20
30

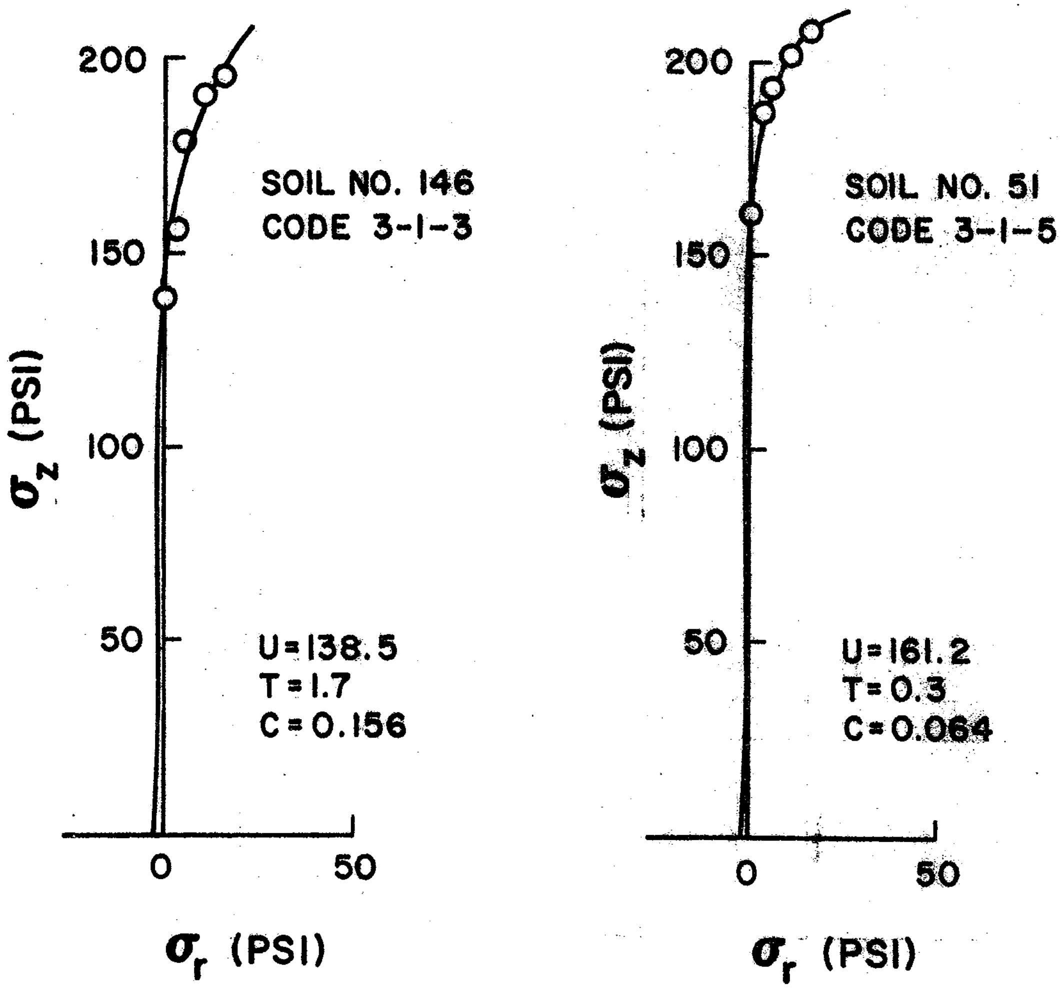


Figure 11: (continued)

Table 5: Summary of parameters by soil characteristic categories

STAB CODE	SB CODE	PI CODE	NO. SAMP.	U AVERAGE	U STD DEV	T AVERAGE	T STD DEV	C AVERAGE	C STD DEV
1	1	1	4	4.3	1.23	1.3	1.99	0.614	0.259
1	1	2	23	6.4	2.24	0.8	0.66	0.510	0.127
1	1	3	55	7.8	3.07	0.9	0.81	0.506	0.165
1	1	4	34	10.5	4.91	1.5	1.70	0.565	0.209
1	1	5	26	18.2	27.45	1.7	3.63	0.667	0.196
1	2	3	9	8.6	3.15	0.5	0.32	0.431	0.125
1	2	4	12	15.2	6.35	0.8	0.45	0.568	0.139
1	2	5	10	14.5	7.04	0.8	0.89	0.607	0.182
1	3	3	5	8.8	2.85	0.6	0.47	0.597	0.182
1	3	4	6	11.2	3.49	0.5	0.37	0.602	0.137
1	3	5	22	26.2	15.10	1.1	0.92	0.618	0.155
1	4	1	2	33.1	27.65	0.1	0.07	0.470	0.176
1	4	3	1	7.7		0.4		0.653	
1	4	4	9	42.2	56.98	0.5	0.47	0.486	0.107
1	4	5	36	34.2	16.98	0.8	1.03	0.525	0.162
1	5	5	1	15.7		1.2		0.703	
2	2	5	1	32.9		6.0		1.000	
3	1	2	1	46.0		6.4		0.622	
3	1	3	1	138.5		1.7		0.156	
3	1	4	5	71.1	53.94	3.6	3.01	0.504	0.244
3	1	5	9	86.8	49.68	7.2	15.93	0.490	0.316
3	2	4	1	108.7		6.6		0.408	

$$C = -0.85 - 0.50X_1^2 + 1.92X_1$$

$$(R^2 = 0.566, \text{ Probability of Type 1 Error} = 0.000) \qquad (5.12)$$

where X_1 = stabilization code, X_2 = soil binder code and X_3 = P1 code. The above three equations did not provide good precision for the estimation of U, T and C from the code classifying material characteristics. Users of FPS-BISTRO should, therefore, run the computer program TRIAXIAL (see Appendix A) to obtain the U, T and C values of the specific construction materials available for designs and then input these U, T and C values into the program FPS-BISTRO. In doing so, however, the user should bear in mind that (1) the standard Texas triaxial test is intended to provide strengths at or near the lowest values likely to occur in the field, and (2) the extrapolation required to obtain estimates of tensile strength should be regarded with caution at this time until the behavior of common base and subbase materials in tension is better understood.

5.3 Checking the Strengths of Materials Against Computed Stresses: Estimated tensile and compressive strengths of common Texas materials from Texas triaxial tests were incorporated into a feasibility check of initial and overlay designs in the FPS-BISTRO program.

Symbols used in Eq. 5.13 and Eq. 5.14 below are defined as follows:

σ_{Ii} - maximum principal stress at point i.

$\sigma_{III,i}$ - minimum principal stress at point i.

H_i - distance from surface to i^{th} layer interface.

U_i - unconfined compressive strength of i^{th} layer.

T_i - lateral tensile strength of i^{th} layer.

C_i - dimensionless parameter of Texas triaxial model of i^{th} layer.

The feasibility evaluation points, i, for strength of materials are shown in Fig. 12.

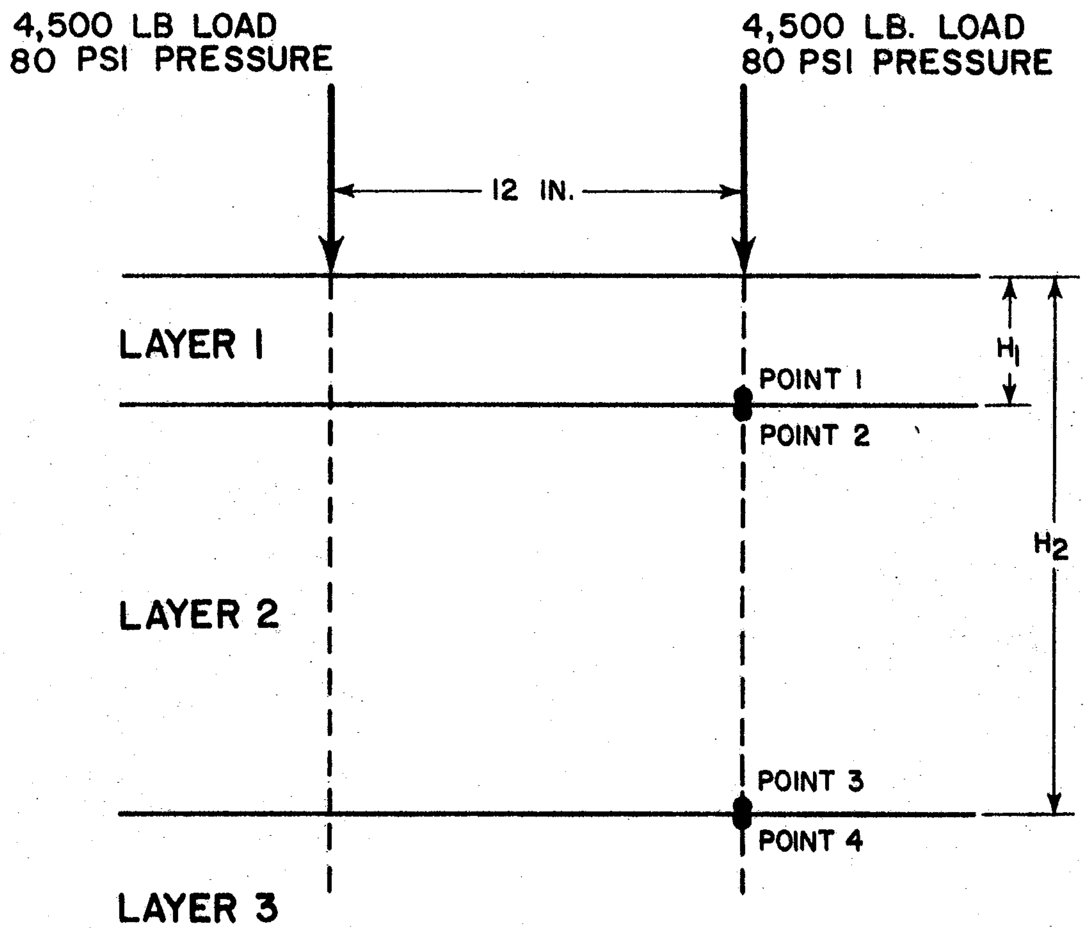


Figure 12: Feasibility evaluation points for strength of materials of a three-layer design.

Check for Tension: Materials satisfying the following conditions are considered feasible for tension. (The terms, $-0.08H_1$ and $-0.08H_2$, are the estimates of the overburden pressure at the first and second interfaces, respectively.)

$$\sigma_{1,1} - 0.08H_1 \leq T_1$$
$$\sigma_{1,2} - 0.08H_1 \leq T_2$$
$$\sigma_{1,3} - 0.08H_2 \leq T_2$$
$$\sigma_{1,4} - 0.08H_2 \leq T_3 \qquad (5.13)$$

Check for Compression: Materials satisfying the following conditions are feasible for compression.

$$-(\sigma_{III,1} - 0.08H_1) \leq U_1 \left[1 - \frac{(\sigma_{1,1} - 0.08H_1)}{T_1}\right]^{C_1}$$
$$-(\sigma_{III,2} - 0.08H_1) \leq U_2 \left[1 - \frac{(\sigma_{1,2} - 0.08H_1)}{T_2}\right]^{C_2}$$
$$-(\sigma_{III,3} - 0.08H_2) \leq U_2 \left[1 - \frac{(\sigma_{1,3} - 0.08H_2)}{T_2}\right]^{C_2}$$
$$-(\sigma_{III,4} - 0.08H_2) \leq U_3 \left[1 - \frac{(\sigma_{1,4} - 0.08H_2)}{T_3}\right]^{C_3} \qquad (5.14)$$

CHAPTER 6

TWO ILLUSTRATIVE EXAMPLES OF THE USE OF FPS-BISTRO

In order to illustrate the use of the computer program, FPS-BISTRO, two examples are presented. Outputs of the two example problems are shown in Appendix B. Input information is also included in the output pages. The differences in input and output informations between the two example problems are listed in Table 6.

The major difference between the two problems is the material used for the second layer. In the first problem, a black base is used, while in the second problem, crushed lime stone base is selected. The cost of the crushed lime stone base ($4.00/cubic yd.) is less than half of the cost of the black base ($11.00/cubic yd.). However, from the output information, the total cost of the optimal design using crushed lime stone base in the second layer ($3.61/square yd.) is greater than half of the total cost of the optimal design using the black base ($5.13/square yd.). The lateral tensile strength of the black base (30 psi) is twice that of the crushed lime stone base (15 psi). This seems to be the reason that the optimal thickness of the crushed lime stone base (19 inches) is more than 4 times the optimal thickness of the black base (4.5 inches).

TABLE 6: Differences on input and output informations between two example FPS-BISTRO problems.

OUTPUT	Problem 1	Problem 2
Max allowed thickness of initial construction (inches)	16.00	22.00
Materials information		
Second layer		
Material	Black Base	Crushed Lime Stone
Cost	11.00	4.00
U	120	110
T	30	15
C	0.8	0.4

OUTPUT	Problem 1	Problem 2
Optimal design		
Initial const. cost	3.90	2.47
Overlay const. cost	1.65	1.56
Salvage value	-0.67	-0.66
Total cost	5.13	3.61
First layer thickness (inch)	7.00	1.00
Second layer thickness (inch)	4.50	19.00
Perf. time (years)		
T(1)	3.9	5.3
T(2)	8.6	10.0
T(3)	14.5	15.3
T(4)	21.2	21.3
Swelling clay loss (serviceability)		
SC(1)	0.39	0.50
SC(2)	0.30	0.26
SC(3)	0.23	0.18
SC(4)	0.14	0.12
Surface curvature index		
SCI(1)	0.114	0.091
SCI(2)	0.091	0.090
SCI(3)	0.076	0.081
SCI(4)	0.067	0.071

TABLE 6: (continued)

OUTPUT (continued)	Problem 1	Problem 2
Principal stresses of init. const. (psi)		
Major stresses at		
Point 1*	24.5	-50.6
Point 2	7.57	-61.5
Point 3	29.5	14.7
Point 4	-1.54	-0.598
Minor stresses at		
Point 1	-21.5	-79.6
Point 2	-21.8	-79.6
Point 3	-7.49	-3.53
Point 4	-7.64	-3.59

* Point number is referred to Figure 12.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

The empirical relationships used in current versions of FPS do not permit the computation of stresses and strains analytically in the pavement structure. This report provides one means for using the theory of linear elasticity to estimate principal stresses and strains at interfacial points under loads. The method is practical and reliable, but may not be economical. To overcome this economical difficulty, a stress-and-strain table of most common basic designs could be constructed by running the revised BISTRO developed in Chapter 3, and storing the results on tape for future use. The multi-dimension interpolation method developed in Chapter 4 could then be applied to evaluate all other trial designs. The computation of the stress-and-strain table would of itself be very expensive, especially for designs with more than three layers. However, it would save much more money in the long run if elasticity theory were applied to FPS and the BISTRO analysis were replaced by the stress-and-strain table.

The feasibility evaluation for strength of materials has been developed in Chapter 5. The stresses are considered in this report. However, the feasibility check will not be complete until a method to consider the strains is fully developed. Furthermore, some effort should be made to refine the "performance equation" (3) now being used. A model based on the fatigue theory seems very adaptable (9).

Because the materials treated in this report differ from ideally elastic materials, the stresses and strains computed from elastic theory should be regarded only as first approximations to the true stresses and strains existing in flexible pavements. But a first approximation is certainly a step away from empiricism and toward a mechanistic structural subsystem of the total pavement design process.

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APPENDIX A

DOCUMENTATION OF THE COMPUTER PROGRAM "TRIAXIAL"

A.1 Program Listing

```
//$OPTIONS
C*******************************************************************C
C                                                                   C
C                                                                   C
C                    ESTIMATE T & C OF TRIAXIAL DATA                C
C                                                                   C
C                         BY FIBONACCI SEARCH                       C
C                                                                   C
C                                                                   C
C*******************************************************************C
      COMMON N,AN,SIGMAR(6),X(6),Y(6),SUMY,TT(20),CC(20),SS(20)
      DIMENSION FIB(20),SIGMAZ(6)
C
C     FIBONACCIAN NUMBER DIVIDED BY 10.
C
      DATA FIB / 0.1, 0.2, 0.3, 0.5, 0.8, 1.3, 2.1, 3.4, 5.5, 8.9,
     *  14.4, 23.3, 37.7, 61.0, 98.7, 159.7, 258.4, 418.1, 676.5,
     *  1094.6 /
    1 FORMAT(46X,2F6.1,           2F7.3)
    2 FORMAT(20X,4I6,2X,2F6.1,2F7.3)
    3 FORMAT(1H1,9(/),20X,
     *            '  SOIL   STAB   SB     PI',24X,'STD.'/ 20X,
     *  '    NO.   CODE  CODE  CODE     U      T       C    ERROR'/)
    4 FORMAT(1H1)
    5 FORMAT(I4,3I2,I5,13F5.0)
C
C     SET TEST NUMBER OF FIBONACCI SEARCH, NFIB.LE.20
C
      NFIB=14
C
C     READ IN TRIAXIAL DATA
C
      LINE=0
      WRITE(6,3)
   20 READ(5,5,END=80) NUMBER,I1,I2,I3,N,U,(SIGMAR(I),SIGMAZ(I),I=1,N)
      AN=N
      IF(LINE.LT.44) GO TO 24
      LINE=0
      WRITE(6,3)
   24 CONTINUE
C
C     CALCULATE Y & SUMY
C
      SUMY=0.
      DO 30 I=1,N
      Y(I)=ALOG(SIGMAZ(I)/U)
   30 SUMY=SUMY+Y(I)
C
C     FIBONACCI SEARCH
C
      CALL ASS(FIB(NFIB),C,V,NFIB)
      M=NFIB-1
      TL=0.
      TR=FIB(NFIB)
      CALL ASS(FIB(M),C,VR,M)
   41 M=M-1
      T=TL+FIB(M)
      CALL ASS(T,C,VL,M)
   42 IF(M.EQ.1) GO TO 44
      IF(VL.GT.VR) GO TO 43
```

```
      TR=TR-FIB(M)
      VR=VL
      GO TO 41
   43 TL=TL+FIB(M)
      VL=VR
      M=M-1
      T=TR-FIB(M)
      CALL ASS(T,C,VR,M)
      GO TO 42
   44 CONTINUE
C
C     FIND MINIMUM STANDARD ERROR
C
      IMIN=1
      SDMIN=SS(1)
      DO 50 I=2,NFIB
      IF(SDMIN.LE.SS(I)) GO TO 50
      IMIN=I
      SDMIN=SS(I)
   50 CONTINUE
      WRITE(6,2) NUMBER,I1,I2,I3,U,TT(IMIN),CC(IMIN),SS(IMIN)
      LINE=LINE+1
      IF(CC(IMIN).LE.1.0) GO TO 20
C
C     CALCULATE A NEW T WITH C=1, WHEN C.GT.1.
C
      C=1.
      SUMR=0.
      SUMZ=0.
      DO 60 I=1,N
      SUMR=SUMR+SIGMAR(I)
      SUMZ=SUMZ+SIGMAZ(I)
   60 CONTINUE
      T=U*SUMR/(SUMZ-AN*U)
      SE=0.
      DO 62 I=1,N
   62 SE=SE+(SIGMAZ(I)-U*(1.+SIGMAR(I)/T))**2
      SE=SQRT(SE/AN)
      WRITE(6,1) U,T,C,SE
      LINE=LINE+1
      GO TO 20
   80 CONTINUE
      WRITE(6,4)
      STOP
      END
C
C     SUBROUTINE ASS(T,C,SE,NASS)
C

      SUBROUTINE ASS(T,C,SE,NASS)
      COMMON N,AN,SIGMAR(6),X(6),Y(6),SUMY,TT(20),CC(20),SS(20)
C
C     CALCULATE X, SUMX & C
C
      SUMX=0.
      DO 10 I=1,N
      X(I)=ALOG(1.+SIGMAR(I)/T)
      SUMX=SUMX+X(I)
   10 CONTINUE
      C=SUMY/SUMX
```

```
C
C       CALCULATE STANDARD ERROR
C
        SE=0.
        DO 20 I=1,N
     20 SE=SE+(Y(I)-X(I)*C)**2
        SE=SQRT(SE/AN)
C
C       ASSIGN T, C & SE VALUES TO ARRAYS
C
        TT(NASS)=T
        CC(NASS)=C
        SS(NASS)=SE
        RETURN
        END

//$DATA
```

A.2 Input Instruction

Each input data card represents one problem. Instructions are as follows:

Field	Column	Format	Comment
1	1 - 4	I4	Soil Number
2	5 - 6	I2	Stabilization Code
3	7 - 8	I2	Soil Binder Code
4	9 - 10	I2	PI Code
5	11 - 15	I5	Number of Data $1 \leq N \leq 6$
6	16 - 20	F5.1	Unconfined Compressive Strength
7	21 - 25	F5.1	σ_{r1}
8	26 - 30	F5.1	σ_{z1}
9	31 - 35	F5.1	σ_{r2}
10	36 - 40	F5.1	σ_{z2}
11	41 - 45	F5.1	σ_{r3}
12	46 - 50	F5.1	σ_{z3}
13	51 - 55	F5.1	σ_{r4}
14	56 - 60	F5.1	σ_{z4}
15	61 - 65	F5.1	σ_{r5}
16	66 - 70	F5.1	σ_{z5}
17	71 - 75	F5.1	σ_{r6}
18	76 - 80	F5.1	σ_{z6}

σ_{ri} and σ_{zi} are radical and vertical normal stresses at i-th data point, $1 \leq i \leq N$, arranged in ascending order of σ_{ri}. σ_r is called the "lateral stress" and σ_z the "vertical stress" in common laboratory language.

A.3 Input Data Listing for 273 Example Problems

```
                 1       1      2      2      3      3      4      4      5      5      6      6      7      7      8
....5....0....5....0....5....0....5....0....5....0....5....0....5....0....5....0
```

100	1	1	1	5	5.2	3.0	8.3	5.0	11.4	10.0	18.3	15.0	24.5	20.0	28.4
145	1	1	1	5	2.7	3.0	12.2	5.0	14.3	10.0	22.1	15.0	24.9	20.0	31.4
166	1	1	1	5	5.3	3.0	15.5	5.0	19.4	10.0	24.3	15.0	32.7	20.0	34.6
167	1	1	1	5	3.9	3.0	13.2	5.0	14.3	10.0	22.5	15.0	25.2	20.0	30.7
11	1	1	2	5	5.2	3.0	10.9	5.0	18.3	10.0	25.4	15.0	23.6	20.0	22.1
16	1	1	2	5	4.6	3.0	11.7	5.0	14.0	10.0	21.4	15.0	28.4	20.0	34.3
39	1	1	2	4	7.4	5.0	18.2	10.0	24.6	15.0	27.6	20.0	30.0		
96	1	1	2	5	3.7	3.0	8.8	5.0	12.4	10.0	17.8	15.0	25.9	20.0	32.5
130	1	1	2	5	9.7	3.0	18.8	5.0	22.0	10.0	27.8	15.0	33.3	20.0	41.9
132	1	1	2	5	6.5	3.0	12.8	5.0	19.7	10.0	27.9	15.0	34.1	20.0	38.5
137	1	1	2	5	9.0	3.0	19.2	5.0	22.6	10.0	28.6	15.0	35.6	20.0	39.8
140	1	1	2	5	6.3	3.0	15.9	5.0	19.3	10.0	27.0	15.0	28.9	20.0	35.2
159	1	1	2	5	5.5	3.0	14.6	5.0	16.8	10.0	16.0	15.0	21.4	20.0	34.2
162	1	1	2	5	5.3	3.0	15.4	5.0	17.3	10.0	23.3	15.0	27.2	20.0	34.1
163	1	1	2	5	3.1	3.0	12.6	5.0	16.2	10.0	21.6	15.0	26.7	20.0	31.1
169	1	1	2	5	5.5	3.0	15.5	5.0	18.5	10.0	22.7	15.0	27.2	20.0	36.2
186	1	1	2	4	2.3	5.0	12.7	10.0	18.8	15.0	24.7	20.0	27.1		
195	1	1	2	5	4.1	3.0	12.8	5.0	15.6	10.0	23.6	15.0	30.6	20.0	35.6
205	1	1	2	5	4.4	3.0	13.4	5.0	16.6	10.0	21.7	15.0	29.9	20.0	29.4
220	1	1	2	5	8.3	3.0	18.6	5.0	14.9	10.0	21.0	15.0	32.1	20.0	36.1
225	1	1	2	5	8.8	3.0	16.6	5.0	18.6	10.0	28.7	15.0	33.4	20.0	35.7
229	1	1	2	5	10.1	3.0	17.9	5.0	20.1	10.0	24.5	15.0	33.7	20.0	44.0
230	1	1	2	5	9.4	3.0	21.6	5.0	18.7	10.0	23.4	15.0	35.0	20.0	37.0
237	1	1	2	5	8.1	3.0	16.1	5.0	19.7	10.0	24.2	15.0	34.2	20.0	39.5
239	1	1	2	5	8.3	3.0	18.0	5.0	21.4	10.0	27.6	15.0	27.4	20.0	35.3
244	1	1	2	5	6.5	3.0	13.2	5.0	15.6	10.0	23.6	15.0	30.6	20.0	34.7
263	1	1	2	5	5.2	3.0	15.3	5.0	17.6	10.0	25.8	15.0	31.0	20.0	32.7
3	1	1	3	3	4.4	5.0	11.9	10.0	18.1	15.0	24.2				
12	1	1	3	4	5.6	3.0	12.0	5.0	14.4	10.0	21.9	15.0	28.2		
13	1	1	3	4	9.2	5.0	17.0	10.0	23.3	15.0	30.4	20.0	33.5		
14	1	1	3	5	9.1	3.0	15.4	5.0	19.1	10.0	26.2	15.0	31.6	20.0	34.0
24	1	1	3	5	14.4	3.0	26.4	5.0	30.4	10.0	41.6	15.0	52.9	20.0	63.1
48	1	1	3	5	3.9	3.0	8.6	5.0	11.9	10.0	19.4	15.0	28.7	20.0	34.6
77	1	1	3	5	4.2	3.0	10.7	5.0	17.4	10.0	23.9	15.0	27.7	20.0	35.9
98	1	1	3	5	3.7	3.0	8.3	5.0	10.9	10.0	14.6	15.0	22.0	20.0	28.7
119	1	1	3	5	4.0	3.0	12.3	5.0	16.9	10.0	23.2	15.0	31.3	20.0	37.2
121	1	1	3	5	3.9	3.0	11.0	5.0	15.3	10.0	22.0	15.0	30.2	20.0	36.1
122	1	1	3	5	6.9	3.0	17.8	5.0	21.0	10.0	27.6	15.0	36.1	20.0	42.1
126	1	1	3	5	7.8	3.0	15.4	5.0	19.4	10.0	27.1	15.0	31.6	20.0	38.3
133	1	1	3	5	11.0	3.0	22.6	5.0	27.6	10.0	30.9	15.0	38.2	20.0	47.4
136	1	1	3	5	10.2	3.0	21.5	5.0	23.7	10.0	31.9	15.0	36.1	20.0	46.6
138	1	1	3	5	11.1	3.0	21.3	5.0	26.1	10.0	33.0	15.0	42.3	20.0	41.7
139	1	1	3	5	7.8	3.0	15.5	5.0	19.3	10.0	27.8	15.0	35.0	20.0	32.0
141	1	1	3	5	5.8	3.0	14.5	5.0	19.0	10.0	22.2	15.0	31.6	20.0	33.2
151	1	1	3	5	6.9	3.0	13.8	5.0	18.5	10.0	23.8	15.0	31.2	20.0	34.1
152	1	1	3	5	7.8	3.0	14.2	5.0	17.5	10.0	27.1	15.0	34.0	20.0	39.5
153	1	1	3	5	1.2	3.0	4.2	5.0	4.3	10.0	5.6	15.0	4.6	20.0	7.1
154	1	1	3	5	4.4	3.0	15.1	5.0	17.3	10.0	25.6	15.0	31.1	20.0	33.2
156	1	1	3	5	10.1	3.0	22.3	5.0	28.1	10.0	36.5	15.0	40.3	20.0	42.9
158	1	1	3	5	3.8	3.0	13.8	5.0	17.5	10.0	23.9	15.0	32.2	20.0	38.1

```
        1    1    2    2    3    3    4    4    5    5    6    6    7    7    8
....5....0....5....0....5....0....5....0....5....0....5....0....5....0....5....0
```

161	1	1	3	5	5.7	3.0	17.0	5.0	20.8	10.0	27.8	15.0	29.5	20.0	38.3
168	1	1	3	5	6.3	3.0	15.5	5.0	19.7	10.0	25.2	15.0	27.6	20.0	37.2
170	1	1	3	5	8.6	3.0	20.8	5.0	22.9	10.0	27.5	15.0	34.2	20.0	37.4
180	1	1	3	5	5.1	3.0	9.6	5.0	19.1	10.0	25.0	15.0	31.0	20.0	34.5
185	1	1	3	5	6.5	3.0	16.9	5.0	21.4	10.0	28.1	15.0	31.6	20.0	33.5
191	1	1	3	4	11.1	3.0	24.0	5.0	26.8	10.0	34.3	15.0	34.1		
197	1	1	3	5	9.3	3.0	21.5	5.0	23.8	10.0	33.8	15.0	39.3	20.0	40.6
198	1	1	3	5	11.8	3.0	23.7	5.0	26.2	10.0	33.1	15.0	40.4	20.0	40.9
199	1	1	3	5	5.1	3.0	15.8	5.0	18.8	10.0	26.5	15.0	29.9	20.0	34.5
200	1	1	3	5	12.1	3.0	21.4	5.0	25.8	10.0	33.5	15.0	43.5	20.0	47.7
201	1	1	3	5	11.1	3.0	21.2	5.0	35.1	10.0	37.0	15.0	39.5	20.0	48.7
202	1	1	3	5	10.2	3.0	23.5	5.0	25.4	10.0	32.5	15.0	36.6	20.0	42.3
206	1	1	3	5	10.6	3.0	21.9	5.0	25.8	10.0	32.9	15.0	40.9	20.0	42.8
207	1	1	3	5	7.5	3.0	22.1	5.0	22.4	10.0	22.9	15.0	36.3	20.0	45.0
223	1	1	3	5	10.3	3.0	18.0	5.0	21.2	10.0	25.2	15.0	34.1	20.0	40.2
224	1	1	3	5	9.0	3.0	18.6	5.0	20.1	10.0	25.6	15.0	34.1	20.0	39.7
232	1	1	3	5	11.1	3.0	22.0	5.0	27.6	10.0	33.3	15.0	40.0	20.0	41.6
234	1	1	3	5	11.4	3.0	23.7	5.0	26.2	10.0	31.5	15.0	40.1	20.0	51.5
235	1	1	3	5	10.4	3.0	17.6	5.0	22.8	10.0	33.0	15.0	38.6	20.0	48.0
236	1	1	3	5	5.8	3.0	8.6	5.0	16.0	10.0	22.3	15.0	29.1	20.0	34.6
238	1	1	3	5	5.6	3.0	16.4	5.0	18.4	10.0	25.5	15.0	32.5	20.0	34.8
241	1	1	3	5	8.1	3.0	19.2	5.0	24.1	10.0	23.5	15.0	33.5	20.0	40.5
242	1	1	3	5	7.1	3.0	15.0	5.0	15.7	10.0	24.6	15.0	28.4	20.0	33.7
245	1	1	3	5	8.0	3.0	16.8	5.0	18.5	10.0	28.6	15.0	33.9	20.0	35.9
250	1	1	3	5	11.4	3.0	25.0	5.0	26.1	10.0	32.9	15.0	40.3	20.0	41.6
251	1	1	3	5	14.2	3.0	28.3	5.0	28.8	10.0	36.3	15.0	43.9	20.0	46.2
253	1	1	3	4	13.3	5.0	31.3	10.0	38.3	15.0	44.0	20.0	49.6		
255	1	1	3	4	5.6	5.0	15.7	10.0	22.0	15.0	30.9	20.0	31.1		
257	1	1	3	5	6.0	3.0	14.3	5.0	18.1	10.0	26.7	15.0	35.5	20.0	40.5
258	1	1	3	5	5.0	3.0	15.8	5.0	16.9	10.0	29.3	15.0	32.3	20.0	35.6
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261	1	1	3	5	5.0	3.0	18.3	5.0	15.7	10.0	23.7	15.0	29.3	20.0	36.2
4	1	1	4	4	4.1	5.0	15.4	10.0	24.2	15.0	30.4	20.0	38.7		
17	1	1	4	4	4.5	5.0	43.9	10.0	73.6	15.0	101.1	20.0	125.1		
18	1	1	4	5	17.8	3.0	25.3	5.0	27.3	10.0	37.8	15.0	46.6	20.0	51.5
19	1	1	4	5	8.6	3.0	14.0	5.0	17.0	10.0	26.7	15.0	32.3	20.0	37.2
23	1	1	4	5	2.8	3.0	11.5	5.0	15.4	10.0	25.1	15.0	34.3	20.0	40.1
25	1	1	4	4	5.0	5.0	15.4	10.0	24.2	15.0	29.4	20.0	33.3		
26	1	1	4	5	11.1	3.0	18.6	5.0	22.3	10.0	30.9	15.0	35.1	20.0	46.1
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81	1	1	4	5	9.2	3.0	14.0	5.0	15.6	10.0	25.2	15.0	33.4	20.0	36.3
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  252 1 5 5      5 15.7  3.0 39.6  5.0 48.9 10.0 71.8 15.0 96.2 20.0122.7
   45 2 2 5      4 32.9  5.0 56.4 10.0 92.6 15.0116.6 20.0139.9
   70 3 1 2      4 46.0  5.0 67.6 10.0 77.9 15.0102.2 20.0109.4
  146 3 1 3      4138.5  3.0155.7  5.0179.3 10.0190.2 15.0194.7
   49 3 1 4      5 75.6  3.0104.2  5.0147.1 10.0152.7 15.0177.0 20.0176.5
   61 3 1 4      4 16.8  5.0 65.4 10.0 95.7 15.0107.1 20.0132.8
   82 3 1 4      4 16.2  5.0 33.7 10.0 54.5 15.0 71.7 20.0 83.7
  113 3 1 4      4133.2  3.0156.0  5.0170.5 10.0202.5 15.0220.4
  114 3 1 4      4113.5  3.0136.9  5.0132.5 10.0166.3 15.0178.1
   41 3 1 5      5143.9  3.0160.5  5.0155.6 10.0160.6 15.0190.9 20.0206.7
   51 3 1 5      4161.2  3.0187.4  5.0194.0 10.0202.0 15.0207.8
   59 3 1 5      4 45.9  3.0 92.5  5.0109.7 10.0138.0 15.0160.4
   73 3 1 5      4 55.6  5.0 91.9 10.0132.1 15.0183.0 20.0197.0
   75 3 1 5      4 95.5  5.0178.6 10.0276.5 15.0267.0 20.0287.8
   78 3 1 5      5139.3  3.0181.3  5.0176.4 10.0271.0 15.0278.5 20.0297.5
  107 3 1 5      5 66.3  3.0117.5  5.0 99.6 10.0116.9 15.0135.4 20.0146.1
  115 3 1 5      5 32.9  3.0 63.5  5.0 81.4 10.0109.0 15.0137.5 20.0156.4
  116 3 1 5      5 40.5  3.0 75.3  5.0 91.6 10.0106.9 15.0142.5 20.0167.1
   43 3 2 4      4108.7  5.0133.2 10.0165.0 15.0174.1 20.0191.3
```

A.4 Output of 273 Example Problems

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
100	1	1	1	5.2	4.4	1.017	0.045
				5.2	4.2	1.000	0.849
145	1	1	1	2.7	0.2	0.526	0.044
166	1	1	1	5.3	0.3	0.448	0.039
167	1	1	1	3.9	0.3	0.484	0.055
11	1	1	2	5.2	0.3	0.386	0.166
16	1	1	2	4.6	1.1	0.675	0.031
39	1	1	2	7.4	0.5	0.383	0.023
96	1	1	2	3.7	1.6	0.826	0.036
130	1	1	2	9.7	1.1	0.476	0.042
132	1	1	2	6.5	1.3	0.651	0.065
137	1	1	2	9.0	0.6	0.416	0.022
140	1	1	2	6.3	0.4	0.433	0.034
159	1	1	2	5.5	0.3	0.374	0.172
162	1	1	2	5.3	0.3	0.426	0.045
163	1	1	2	3.1	0.2	0.500	0.018
169	1	1	2	5.5	0.3	0.422	0.065
186	1	1	2	2.3	0.3	0.594	0.027
195	1	1	2	4.1	0.6	0.613	0.025
205	1	1	2	4.4	0.3	0.463	0.052
220	1	1	2	8.3	1.6	0.547	0.155
225	1	1	2	8.8	1.3	0.516	0.048
229	1	1	2	10.1	2.7	0.656	0.077
230	1	1	2	9.4	0.6	0.374	0.131
237	1	1	2	8.1	1.4	0.572	0.053
239	1	1	2	8.3	0.3	0.328	0.055
244	1	1	2	6.5	1.7	0.666	0.027
263	1	1	2	5.2	0.3	0.444	0.037
3	1	1	3	4.4	2.1	0.812	0.006
12	1	1	3	5.6	1.5	0.670	0.024
13	1	1	3	9.2	3.3	0.674	0.025
14	1	1	3	9.1	1.6	0.520	0.026
24	1	1	3	14.4	1.9	0.597	0.027
48	1	1	3	3.9	2.4	0.987	0.022
77	1	1	3	4.2	0.8	0.656	0.075
98	1	1	3	3.7	1.9	0.815	0.064
119	1	1	3	4.0	0.6	0.629	0.027
121	1	1	3	3.9	0.9	0.709	0.023
122	1	1	3	6.9	0.6	0.505	0.037
126	1	1	3	7.8	1.2	0.550	0.018
133	1	1	3	11.0	0.6	0.393	0.059
136	1	1	3	10.2	0.8	0.445	0.052
138	1	1	3	11.1	0.8	0.425	0.043
139	1	1	3	7.8	0.8	0.466	0.076

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
141	1	1	3	5.8	0.5	0.474	0.059
151	1	1	3	6.9	1.1	0.549	0.034
152	1	1	3	7.8	2.4	0.737	0.022
153	1	1	3	1.2	0.1	0.322	0.144
154	1	1	3	4.4	0.2	0.441	0.039
156	1	1	3	10.1	0.3	0.350	0.034
158	1	1	3	3.8	0.4	0.584	0.034
161	1	1	3	5.7	0.2	0.398	0.048
168	1	1	3	6.3	0.5	0.460	0.058
170	1	1	3	8.6	0.3	0.347	0.038
180	1	1	3	5.1	1.3	0.707	0.138
185	1	1	3	6.5	0.2	0.361	0.032
191	1	1	3	11.1	0.1	0.230	0.040
197	1	1	3	9.3	0.4	0.384	0.041
198	1	1	3	11.8	0.5	0.344	0.033
199	1	1	3	5.1	0.2	0.411	0.023
200	1	1	3	12.1	1.6	0.532	0.023
201	1	1	3	11.1	0.4	0.369	0.113
202	1	1	3	10.2	0.3	0.331	0.030
206	1	1	3	10.6	0.6	0.401	0.024
207	1	1	3	7.5	0.3	0.393	0.151
223	1	1	3	10.3	1.8	0.531	0.053
224	1	1	3	9.0	1.0	0.473	0.059
232	1	1	3	11.1	0.5	0.364	0.029
234	1	1	3	11.4	0.9	0.451	0.073
235	1	1	3	10.4	2.4	0.681	0.028
236	1	1	3	5.8	3.6	0.972	0.120
238	1	1	3	5.6	0.3	0.434	0.038
241	1	1	3	8.1	0.4	0.388	0.104
242	1	1	3	7.1	1.2	0.540	0.056
245	1	1	3	8.0	1.0	0.509	0.051
250	1	1	3	11.4	0.3	0.309	0.042
251	1	1	3	14.2	0.4	0.298	0.045
253	1	1	3	13.3	0.5	0.352	0.012
255	1	1	3	5.6	1.0	0.582	0.057
257	1	1	3	6.0	1.1	0.652	0.018
258	1	1	3	5.0	0.4	0.511	0.076
259	1	1	3	4.6	0.1	0.370	0.066
261	1	1	3	5.0	0.2	0.410	0.121
4	1	1	4	4.1	0.9	0.707	0.018
17	1	1	4	4.5	0.3	0.791	0.005
18	1	1	4	17.8	4.7	0.653	0.029
19	1	1	4	8.6	3.2	0.755	0.035
23	1	1	4	2.8	0.5	0.721	0.019

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
25	1	1	4	5.0	0.9	0.613	0.032
26	1	1	4	11.1	2.3	0.605	0.039
40	1	1	4	8.3	2.2	0.690	0.071
50	1	1	4	3.8	1.3	0.749	0.033
74	1	1	4	7.6	0.1	0.353	0.057
79	1	1	4	3.5	0.1	0.485	0.141
80	1	1	4	11.6	4.2	0.783	0.034
81	1	1	4	9.2	5.6	0.940	0.054
86	1	1	4	8.1	4.3	0.910	0.010
94	1	1	4	14.5	3.2	0.773	0.070
97	1	1	4	7.4	8.9	1.436	0.071
				7.4	4.8	1.000	1.562
134	1	1	4	13.7	0.1	0.289	0.033
155	1	1	4	13.3	0.3	0.316	0.048
171	1	1	4	9.2	0.3	0.403	0.031
172	1	1	4	8.7	0.4	0.413	0.049
173	1	1	4	5.2	0.3	0.447	0.035
174	1	1	4	9.6	0.6	0.450	0.027
177	1	1	4	13.4	0.3	0.416	0.068
178	1	1	4	7.6	0.4	0.399	0.049
181	1	1	4	14.2	2.0	0.564	0.105
182	1	1	4	12.6	0.4	0.501	0.031
184	1	1	4	15.9	0.2	0.346	0.038
208	1	1	4	15.7	0.3	0.418	0.054
240	1	1	4	11.8	0.3	0.321	0.053
249	1	1	4	17.8	0.1	0.230	0.061
254	1	1	4	19.8	4.1	0.859	0.173
256	1	1	4	19.1	0.6	0.366	0.031
260	1	1	4	5.4	0.6	0.509	0.055
262	1	1	4	17.2	0.8	0.425	0.066
8	1	1	5	5.8	0.7	0.786	0.013
20	1	1	5	6.6	7.5	1.350	0.083
				6.6	4.4	1.000	1.782
21	1	1	5	12.1	0.5	0.627	0.019
46	1	1	5	149.2	61.0	2.639	0.114
				149.2	18.2	1.000	24.878
52	1	1	5	7.8	0.6	0.749	0.037
58	1	1	5	5.5	0.5	0.518	0.018
63	1	1	5	9.4	1.1	0.907	0.018
65	1	1	5	5.0	0.8	0.966	0.027
66	1	1	5	9.2	1.0	0.766	0.034
72	1	1	5	14.1	1.1	0.774	0.015
83	1	1	5	23.9	1.8	0.735	0.048
118	1	1	5	18.6	0.7	0.588	0.026

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
120	1	1	5	28.1	61.0	5.215	0.553
				28.1	6.4	1.000	25.388
123	1	1	5	14.3	0.5	0.606	0.037
125	1	1	5	24.0	1.0	0.503	0.034
157	1	1	5	21.0	0.4	0.398	0.095
160	1	1	5	16.3	0.5	0.489	0.049
179	1	1	5	12.8	0.8	0.674	0.235
183	1	1	5	6.3	0.2	0.632	0.064
188	1	1	5	9.7	0.2	0.550	0.038
214	1	1	5	13.5	0.4	0.485	0.034
215	1	1	5	11.2	0.2	0.517	0.009
218	1	1	5	17.4	0.2	0.401	0.049
246	1	1	5	14.3	0.1	0.315	0.078
266	1	1	5	11.2	0.8	0.652	0.072
270	1	1	5	5.7	0.4	0.694	0.083
54	1	2	3	7.6	0.8	0.704	0.024
124	1	2	3	4.4	0.1	0.357	0.050
127	1	2	3	6.2	0.4	0.441	0.068
131	1	2	3	13.8	0.7	0.337	0.031
203	1	2	3	12.1	0.7	0.439	0.048
204	1	2	3	11.1	0.3	0.400	0.053
233	1	2	3	7.1	0.9	0.542	0.059
243	1	2	3	9.1	0.1	0.294	0.101
248	1	2	3	6.0	0.1	0.362	0.064
1	1	2	4	11.9	0.9	0.768	0.033
28	1	2	4	17.9	1.5	0.689	0.047
42	1	2	4	2.8	0.9	0.786	0.068
47	1	2	4	12.1	0.7	0.623	0.034
53	1	2	4	24.2	0.9	0.556	0.050
62	1	2	4	15.0	0.8	0.526	0.071
67	1	2	4	19.0	1.1	0.578	0.015
76	1	2	4	13.5	1.0	0.555	0.062
99	1	2	4	18.1	1.4	0.567	0.027
189	1	2	4	18.9	0.1	0.358	0.023
193	1	2	4	5.9	0.1	0.471	0.104
273	1	2	4	22.6	0.3	0.339	0.046
2	1	2	5	11.5	1.2	0.849	0.037
9	1	2	5	17.0	0.6	0.605	0.057
27	1	2	5	19.2	0.4	0.344	0.131
30	1	2	5	13.8	0.7	0.573	0.041
31	1	2	5	18.1	0.9	0.649	0.034
44	1	2	5	6.5	0.6	0.798	0.022
91	1	2	5	7.8	3.2	0.758	0.068
143	1	2	5	19.1	0.1	0.351	0.066

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
190	1	2	5	27.3	0.4	0.431	0.043
247	1	2	5	4.4	0.3	0.713	0.071
7	1	3	3	4.8	0.9	0.757	0.027
33	1	3	3	7.1	0.2	0.556	0.067
57	1	3	3	11.0	1.2	0.813	0.032
213	1	3	3	9.3	0.1	0.466	0.198
228	1	3	3	11.7	0.7	0.395	0.088
32	1	3	4	10.7	1.0	0.780	0.013
34	1	3	4	7.5	0.4	0.615	0.051
37	1	3	4	17.6	0.9	0.579	0.031
55	1	3	4	9.0	0.5	0.721	0.047
135	1	3	4	11.9	0.1	0.401	0.055
144	1	3	4	10.3	0.2	0.518	0.138
5	1	3	5	19.2	0.5	0.498	0.023
6	1	3	5	4.9	0.2	0.633	0.030
10	1	3	5	7.9	2.2	1.169	0.098
				7.9	1.5	1.000	3.227
35	1	3	5	23.2	0.8	0.666	0.058
36	1	3	5	21.1	1.4	0.734	0.037
38	1	3	5	4.9	2.5	0.853	0.037
56	1	3	5	7.2	0.4	0.664	0.053
60	1	3	5	25.7	1.0	0.589	0.049
64	1	3	5	31.4	1.3	0.583	0.011
68	1	3	5	24.9	1.3	0.618	0.022
69	1	3	5	22.2	0.7	0.609	0.069
71	1	3	5	23.7	0.9	0.618	0.036
87	1	3	5	52.6	2.9	0.665	0.045
95	1	3	5	12.2	0.8	0.746	0.023
101	1	3	5	43.3	1.8	0.599	0.060
104	1	3	5	37.8	0.3	0.386	0.172
105	1	3	5	47.3	2.0	0.677	0.039
106	1	3	5	58.9	3.4	0.748	0.045
164	1	3	5	38.9	0.1	0.318	0.040
212	1	3	5	20.0	0.2	0.450	0.068
216	1	3	5	22.3	0.1	0.383	0.054
265	1	3	5	27.4	0.6	0.556	0.119
192	1	4	1	13.5	0.1	0.594	0.134
231	1	4	1	52.6	0.2	0.345	0.059
22	1	4	3	7.7	0.4	0.653	0.048
15	1	4	4	11.2	0.5	0.685	0.026
92	1	4	4	59.5	1.3	0.500	0.082
109	1	4	4	16.3	0.2	0.533	0.046
111	1	4	4	22.0	0.2	0.503	0.083
142	1	4	4	16.7	0.2	0.505	0.042

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
194	1	4	4	22.3	0.1	0.383	0.044
211	1	4	4	189.5	1.3	0.306	0.094
226	1	4	4	21.8	0.5	0.539	0.067
264	1	4	4	20.5	0.2	0.423	0.039
29	1	4	5	8.2	0.8	0.857	0.062
84	1	4	5	28.0	0.8	0.582	0.052
85	1	4	5	19.0	2.0	0.894	0.061
88	1	4	5	72.7	4.8	0.789	0.064
89	1	4	5	56.6	3.4	0.766	0.022
90	1	4	5	46.0	1.2	0.545	0.018
93	1	4	5	49.0	1.0	0.511	0.048
102	1	4	5	74.9	0.8	0.392	0.036
103	1	4	5	43.0	2.2	0.745	0.060
108	1	4	5	37.0	0.6	0.521	0.070
110	1	4	5	55.4	0.3	0.355	0.036
112	1	4	5	39.6	0.1	0.318	0.034
117	1	4	5	59.7	0.3	0.365	0.013
128	1	4	5	18.8	0.2	0.540	0.049
129	1	4	5	25.5	0.1	0.426	0.074
147	1	4	5	36.5	0.3	0.449	0.024
148	1	4	5	12.3	0.1	0.524	0.086
149	1	4	5	23.4	0.1	0.414	0.030
150	1	4	5	25.9	0.5	0.454	0.085
165	1	4	5	33.3	0.2	0.414	0.051
175	1	4	5	19.9	0.1	0.445	0.057
176	1	4	5	8.8	0.1	0.509	0.192
187	1	4	5	35.2	0.1	0.369	0.051
196	1	4	5	21.6	0.1	0.395	0.029
209	1	4	5	51.4	0.7	0.507	0.042
210	1	4	5	31.3	0.5	0.534	0.058
217	1	4	5	42.8	0.2	0.388	0.030
219	1	4	5	36.3	0.6	0.541	0.058
221	1	4	5	28.7	0.1	0.380	0.015
222	1	4	5	15.5	0.2	0.565	0.120
227	1	4	5	43.4	0.8	0.559	0.067
267	1	4	5	24.5	0.2	0.456	0.095
268	1	4	5	14.8	0.1	0.455	0.090
269	1	4	5	49.8	1.0	0.494	0.049
271	1	4	5	26.2	2.6	1.044	0.255
				26.2	2.3	1.000	20.696
272	1	4	5	16.6	0.1	0.438	0.077
252	1	5	5	15.7	1.2	0.703	0.036
45	2	2	5	32.9	6.8	1.074	0.044
				32.9	6.0	1.000	3.473

SOIL NO.	STAB CODE	SB CODE	PI CODE	U	T	C	STD. ERROR
70	3	1	2	46.0	6.4	0.622	0.041
146	3	1	3	138.5	1.7	0.156	0.032
49	3	1	4	75.6	0.8	0.274	0.077
61	3	1	4	16.8	0.4	0.522	0.034
82	3	1	4	16.2	3.8	0.912	0.033
113	3	1	4	133.2	6.0	0.409	0.011
114	3	1	4	113.5	7.1	0.405	0.040
41	3	1	5	143.9	61.0	1.204	0.042
				143.9	49.3	1.000	7.151
51	3	1	5	161.2	0.3	0.064	0.002
59	3	1	5	45.9	0.5	0.363	0.004
73	3	1	5	55.6	6.7	0.949	0.047
75	3	1	5	95.5	0.8	0.353	0.085
78	3	1	5	139.3	4.7	0.480	0.076
107	3	1	5	66.3	0.2	0.161	0.085
115	3	1	5	32.9	1.3	0.560	0.015
116	3	1	5	40.5	1.2	0.479	0.051
43	3	2	4	108.7	6.6	0.408	0.025

APPENDIX B

OUTPUT OF TWO EXAMPLE FOR FPS-BISTRO

B.1 Output of Problem No. 1

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	1

****

COMMENTS ABOUT THIS PROBLEM

****

BASIC DESIGN CRITERIA
****

LENGTH OF THE ANALYSIS PERIOD (YEARS)	20.0
MINIMUM TIME TO FIRST OVERLAY (YEARS)	3.0
MINIMUM TIME BETWEEN OVERLAYS (YEARS)	3.0
MINIMUM SERVICEABILITY INDEX P2	3.0
DESIGN CONFIDENCE LEVEL	D
INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)	6.0

PROGRAM CONTROLS AND CONSTRAINTS
****

NUMBER OF SUMMARY OUTPUT PAGES DESIRED (8 DESIGNS/PAGE)	3
READ IN DATA OF TWENTY-FIVE BASIC DESIGNS.	
ACCURACY LEVEL FOR ANALYSIS OF LINEAR ELASTICITY	EXELLANT
MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)	4.00
MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)	16.0
ACCUMULATED MAX DEPTH OF ALL OVERLAYS (INCHES) (EXCLUDING LEVEL-UP)	8.0

TRAFFIC DATA
****

ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)	10000.
ADT AT END OF TWENTY YEARS (VEHICLES/DAY)	20000.
ONE-DIRECTION 20.-YEAR ACCUMULATED NO. OF EQUIVALENT 18-KSA	5000000.
AVERAGE APPROACH SPEED TO THE OVERLAY ZONE(MPH)	60.0
AVERAGE SPEED THROUGH OVERLAY ZONE (OVERLAY DIRECTION) (MPH)	30.0
AVERAGE SPEED THROUGH OVERLAY ZONE (NON-OVERLAY DIRECTION) (MPH)	60.0
PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)	5.5
PERCENT TRUCKS IN ADT	8.0

ENVIRONMENT AND SUBGRADE
****

DISTRICT TEMPERATURE CONSTANT	22.0
SWELLING PROBABILITY	0.90
POTENTIAL VERTICAL RISE (INCHES)	4.00
SWELLING RATE CONSTANT	0.10

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	2

INPUT DATA CONTINUED

CONSTRUCTION AND MAINTENANCE DATA
****

SERVICEABILITY INDEX OF THE INITIAL STRUCTURE	4.2
SERVICEABILITY INDEX P1 AFTER AN OVERLAY	4.2
MINIMUM OVERLAY THICKNESS (INCHES)	2.0
OVERLAY CONSTRUCTION TIME (HOURS/DAY)	10.0
ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)	1.80
ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)	75.0
WIDTH OF EACH LANE (FEET)	12.0
FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE-MILE)	50.00
ANNUAL INCREMENTAL INCREASE IN MAINTENANCE COST (DOLLARS/LANE-MILE)	20.00

DETOUR DESIGN FOR OVERLAYS
****

TRAFFIC MODEL USED DURING OVERLAYING	3
TOTAL NUMBER OF LANES OF THE FACILITY	4
NUMBER OF OPEN LANES IN RESTRICTED ZONE (OVERLAY DIRECTION)	1
NUMBER OF OPEN LANES IN RESTRICTED ZONE (NON-OVERLAY DIRECTION)	2
DISTANCE TRAFFIC IS SLOWED (OVERLAY DIRECTION) (MILES)	0.50
DISTANCE TRAFFIC IS SLOWED (NON-OVERLAY DIRECTION) (MILES)	0.50
DETOUR DISTANCE AROUND THE OVERLAY ZONE (MILES)	0.0

MATERIALS INFORMATION
****

LAYER	MATERIALS CODE	NAME	COST PER CY	MIN. DEPTH	MAX. DEPTH	SALVAGE, PCT.
1	A	ASPHALTIC CONCRETE	13.00	1.00	8.00	25.00
2	B	BLACK BASE	11.00	4.00	20.00	70.00

LAYER	MATERIALS CODE	NAME	ELASTIC MODULUS	POISSON RATIO	TEXAS TRIAXIAL TEST U	T	C
1	A	ASPHALTIC CONCRETE	240000.	0.50	200.0	40.0	0.800
2	B	BLACK BASE	150000.	0.50	120.0	30.0	0.800
		SUBGRADE	24000.	0.50	16.0	4.0	0.600

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	3

25 BASIC DESIGNS CALCULATED BY LINEAR ELASTIC PROGRAM BISTRO

****

NO	D(1)	D(2)	SCI	DEPTH	LAYER	SIGMA1	SIGMA3	EPSLN1	EPSLN3
1	1.0	4.0	0.323						
				1.0	1	-0.721E 02	-0.781E 02	0.239E-04	-0.137E-04
				1.0	2	-0.728E 02	-0.778E 02	0.317E-04	-0.179E-04
				5.0	2	0.854E 02	-0.252E 02	0.417E-03	-0.689E-03
				5.0	3	-0.747E 01	-0.253E 02	0.417E-03	-0.701E-03
2	2.0	4.0	0.268						
				2.0	1	-0.170E 02	-0.663E 02	0.106E-03	-0.203E-03
				2.0	2	-0.354E 02	-0.665E 02	0.106E-03	-0.206E-03
				6.0	2	0.705E 02	-0.198E 02	0.342E-03	-0.560E-03
				6.0	3	-0.529E 01	-0.200E 02	0.342E-03	-0.575E-03
3	4.0	4.0	0.186						
				4.0	1	0.223E 02	-0.420E 02	0.146E-03	-0.256E-03
				4.0	2	-0.164E 01	-0.422E 02	0.146E-03	-0.260E-03
				8.0	2	0.488E 02	-0.130E 02	0.234E-03	-0.383E-03
				8.0	3	-0.306E 01	-0.132E 02	0.234E-03	-0.399E-03
4	8.0	4.0	0.104						
				8.0	1	0.244E 02	-0.173E 02	0.965E-04	-0.164E-03
				8.0	2	0.894E 01	-0.176E 02	0.965E-04	-0.168E-03
				12.0	2	0.272E 02	-0.684E 01	0.127E-03	-0.214E-03
				12.0	3	-0.136E 01	-0.699E 01	0.127E-03	-0.224E-03
5	16.0	4.0	0.061						
				16.0	1	0.139E 02	-0.530E 01	0.432E-04	-0.765E-04
				16.0	2	0.676E 01	-0.543E 01	0.432E-04	-0.787E-04
				20.0	2	0.121E 02	-0.288E 01	0.540E-04	-0.962E-04
				20.0	3	-0.470E 00	-0.294E 01	0.540E-04	-0.100E-03
6	1.0	8.0	0.172						
				1.0	1	-0.663E 02	-0.793E 02	0.314E-04	-0.502E-04
				1.0	2	-0.708E 02	-0.795E 02	0.343E-04	-0.531E-04
				9.0	2	0.456E 02	-0.119E 02	0.218E-03	-0.357E-03
				9.0	3	-0.268E 01	-0.121E 02	0.218E-03	-0.371E-03
7	2.0	8.0	0.155						
				2.0	1	-0.241E 02	-0.712E 02	0.102E-03	-0.193E-03
				2.0	2	-0.417E 02	-0.713E 02	0.102E-03	-0.195E-03
				10.0	2	0.394E 02	-0.101E 02	0.187E-03	-0.307E-03
				10.0	3	-0.215E 01	-0.103E 02	0.187E-03	-0.321E-03
8	4.0	8.0	0.125						
				4.0	1	0.890E 01	-0.472E 02	0.127E-03	-0.223E-03
				4.0	2	-0.120E 02	-0.474E 02	0.127E-03	-0.227E-03
				12.0	2	0.298E 02	-0.747E 01	0.140E-03	-0.233E-03
				12.0	3	-0.148E 01	-0.764E 01	0.140E-03	-0.245E-03
9	8.0	8.0	0.084						
				8.0	1	0.142E 02	-0.207E 02	0.814E-04	-0.136E-03
				8.0	2	0.131E 01	-0.210E 02	0.814E-04	-0.142E-03
				16.0	2	0.187E 02	-0.455E 01	0.852E-04	-0.147E-03
				16.0	3	-0.816E 00	-0.465E 01	0.852E-04	-0.154E-03

****

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	4

25 BASIC DESIGNS CALCULATED BY LINEAR ELASTIC PROGRAM BISTRO

NO	D(1)	D(2)	SCI	DEPTH	LAYER	SIGMA1	SIGMA3	EPSLN1	EPSLN3
10	16.0	8.0	0.057						
				16.0	1	0.912E 01	-0.672E 01	0.359E-04	-0.631E-04
				16.0	2	0.330E 01	-0.690E 01	0.359E-04	-0.661E-04
				24.0	2	0.933E 01	-0.219E 01	0.408E-04	-0.744E-04
				24.0	3	-0.337E 00	-0.222E 01	0.408E-04	-0.771E-04
11	1.0	12.0	0.119						
				1.0	1	-0.591E 02	-0.795E 02	0.431E-04	-0.843E-04
				1.0	2	-0.667E 02	-0.795E 02	0.431E-04	-0.849E-04
				13.0	2	0.278E 02	-0.695E 01	0.130E-03	-0.217E-03
				13.0	3	-0.136E 01	-0.711E 01	0.130E-03	-0.229E-03
12	2.0	12.0	0.115						
				2.0	1	-0.214E 02	-0.720E 02	0.111E-03	-0.206E-03
				2.0	2	-0.403E 02	-0.721E 02	0.111E-03	-0.206E-03
				14.0	2	0.249E 02	-0.614E 01	0.116E-03	-0.195E-03
				14.0	3	-0.115E 01	-0.628E 01	0.116E-03	-0.205E-03
13	4.0	12.0	0.101						
				4.0	1	0.687E 01	-0.486E 02	0.127E-03	-0.220E-03
				4.0	2	-0.139E 02	-0.487E 02	0.127E-03	-0.222E-03
				16.0	2	0.201E 02	-0.488E 01	0.919E-04	-0.157E-03
				16.0	3	-0.866E 00	-0.499E 01	0.919E-04	-0.166E-03
14	8.0	12.0	0.074						
				8.0	1	0.108E 02	-0.221E 02	0.779E-04	-0.128E-03
				8.0	2	-0.137E 01	-0.224E 02	0.779E-04	-0.132E-03
				20.0	2	0.136E 02	-0.325E 01	0.608E-04	-0.108E-03
				20.0	3	-0.543E 00	-0.332E 01	0.608E-04	-0.113E-03
15	16.0	12.0	0.055						
				16.0	1	0.696E 01	-0.761E 01	0.333E-04	-0.578E-04
				16.0	2	0.162E 01	-0.779E 01	0.333E-04	-0.608E-04
				28.0	2	0.737E 01	-0.172E 01	0.318E-04	-0.590E-04
				28.0	3	-0.259E 00	-0.174E 01	0.318E-04	-0.608E-04
16	1.0	16.0	0.099						
				1.0	1	-0.534E 02	-0.796E 02	0.570E-04	-0.107E-03
				1.0	2	-0.632E 02	-0.796E 02	0.570E-04	-0.107E-03
				17.0	2	0.188E 02	-0.458E 01	0.859E-04	-0.148E-03
				17.0	3	-0.822E 00	-0.468E 01	0.859E-04	-0.156E-03
17	2.0	16.0	0.098						
				2.0	1	-0.185E 02	-0.723E 02	0.119E-03	-0.217E-03
				2.0	2	-0.387E 02	-0.723E 02	0.119E-03	-0.218E-03
				18.0	2	0.172E 02	-0.414E 01	0.780E-04	-0.135E-03
				18.0	3	-0.715E 00	-0.424E 01	0.780E-04	-0.142E-03
18	4.0	16.0	0.090						
				4.0	1	0.700E 01	-0.491E 02	0.128E-03	-0.222E-03
				4.0	2	-0.140E 02	-0.492E 02	0.128E-03	-0.223E-03
				20.0	2	0.144E 02	-0.343E 01	0.646E-04	-0.114E-03
				20.0	3	-0.566E 00	-0.351E 01	0.646E-04	-0.119E-03

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	7

SUMMARY OF THE BEST DESIGN STRATEGIES
IN ORDER OF INCREASING TOTAL COST

	1	2	3	4	5	6	7	8
MATERIAL ARRANGEMENT	AB	AB	AB	AB	AB	AB	AB	AB
INIT. CONST. COST	3.90	3.97	3.93	4.00	3.92	3.87	3.94	3.90
OVERLAY CONST. COST	1.65	1.68	1.63	1.68	1.91	2.15	1.87	2.13
USER COST	0.09	0.09	0.09	0.09	0.11	0.12	0.11	0.12
ROUTINE MAINT. COST	0.15	0.15	0.15	0.15	0.15	0.14	0.15	0.14
SALVAGE VALUE	-0.67	-0.76	-0.65	-0.74	-0.82	-1.02	-0.80	-1.00
TOTAL COST	5.13	5.14	5.15	5.19	5.26	5.26	5.27	5.29
NUMBER OF LAYERS	2	2	2	2	2	2	2	2
LAYER DEPTH (INCHES)								
D(1)	7.00	5.50	7.50	6.00	4.50	1.00	5.00	1.50
D(2)	4.50	6.50	4.00	6.00	7.50	11.50	7.00	11.00
NO.OF PERF.PERIODS	4	4	4	4	4	5	4	5
PERF. TIME (YEARS)								
T(1)	3.9	3.7	4.1	3.9	3.5	3.6	3.6	3.5
T(2)	8.6	8.1	9.0	8.4	7.6	7.0	7.8	7.1
T(3)	14.5	13.7	15.0	14.1	13.6	11.2	13.3	11.4
T(4)	21.2	20.2	21.8	20.8	20.5	16.4	20.4	16.8
T(5)						22.5		23.1
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)								
O(1)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
O(2)	2.5	2.5	2.5	2.5	3.5	2.5	2.5	2.5
O(3)	2.5	2.5	2.5	2.5	2.5	2.5	3.5	2.5
O(4)						2.5		2.5
SWELLING CLAY LOSS (SERVICEABILITY)								
SC(1)	0.39	0.38	0.41	0.39	0.36	0.36	0.37	0.36
SC(2)	0.30	0.29	0.31	0.30	0.28	0.24	0.29	0.25
SC(3)	0.23	0.23	0.22	0.23	0.25	0.20	0.23	0.21
SC(4)	0.14	0.15	0.13	0.14	0.15	0.16	0.16	0.16
SC(5)						0.11		0.10

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
1	2		3210	12	SH360	03/01/72	152	8

SUMMARY OF THE BEST DESIGN STRATEGIES
IN ORDER OF INCREASING TOTAL COST

	9	10	11	12
MATERIAL ARRANGEMENT	AB	AB	AB	AB
INIT. CONST. COST	3.99	3.93	3.89	3.96
OVERLAY CONST. COST	1.97	2.10	2.02	2.08
USER COST	0.11	0.12	0.11	0.12
ROUTINE MAINT. COST	0.15	0.14	0.15	0.14
SALVAGE VALUE	-0.92	-0.98	-0.84	-0.96
TOTAL COST	5.29	5.31	5.33	5.34
NUMBER OF LAYERS	2	2	2	2
LAYER DEPTH (INCHES)				
D(1)	3.00	2.00	4.00	2.50
D(2)	9.50	10.50	8.00	10.00
NO.OF PERF.PERIODS	4	5	4	5
PERF. TIME (YEARS)				
T(1)	3.6	3.5	3.5	3.5
T(2)	8.0	7.2	7.4	7.3
T(3)	13.6	11.7	13.3	12.0
T(4)	20.2	17.3	20.1	17.8
T(5)		23.8		24.5
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)				
O(1)	3.5	2.5	2.5	2.5
O(2)	2.5	2.5	3.5	2.5
O(3)	2.5	2.5	2.5	2.5
O(4)		2.5		2.5
SWELLING CLAY LOSS (SERVICEABILITY)				
SC(1)	0.36	0.36	0.35	0.36
SC(2)	0.30	0.26	0.28	0.27
SC(3)	0.23	0.22	0.25	0.22
SC(4)	0.15	0.16	0.16	0.16
SC(5)		0.10		0.10

THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS 12

B.2 Output of Problem No. 2

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
2	2	ABC	3210	12	SH360	03/01/72	152	1

****

COMMENTS ABOUT THIS PROBLEM

****

BASIC DESIGN CRITERIA
****

LENGTH OF THE ANALYSIS PERIOD (YEARS)	20.0
MINIMUM TIME TO FIRST OVERLAY (YEARS)	3.0
MINIMUM TIME BETWEEN OVERLAYS (YEARS)	3.0
MINIMUM SERVICEABILITY INDEX P2	3.0
DESIGN CONFIDENCE LEVEL	D
INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)	6.0

PROGRAM CONTROLS AND CONSTRAINTS
****

NUMBER OF SUMMARY OUTPUT PAGES DESIRED (8 DESIGNS/PAGE)	3
MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)	4.00
MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)	22.0
ACCUMULATED MAX DEPTH OF ALL OVERLAYS (INCHES) (EXCLUDING LEVEL-UP)	8.0

TRAFFIC DATA
****

ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)	10000.
ADT AT END OF TWENTY YEARS (VEHICLES/DAY)	20000.
ONE-DIRECTION 20.-YEAR ACCUMULATED NO. OF EQUIVALENT 18-KSA	5000000.
AVERAGE APPROACH SPEED TO THE OVERLAY ZONE(MPH)	60.0
AVERAGE SPEED THROUGH OVERLAY ZONE (OVERLAY DIRECTION) (MPH)	30.0
AVERAGE SPEED THROUGH OVERLAY ZONE (NON-OVERLAY DIRECTION) (MPH)	60.0
PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)	5.5
PERCENT TRUCKS IN ADT	8.0

ENVIRONMENT AND SUBGRADE
****

DISTRICT TEMPERATURE CONSTANT	22.0
SWELLING PROBABILITY	0.90
POTENTIAL VERTICAL RISE (INCHES)	4.00
SWELLING RATE CONSTANT	0.10

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
2	2	ABC	3210	12	SH360	03/01/72	152	2

INPUT DATA CONTINUED

CONSTRUCTION AND MAINTENANCE DATA
****

SERVICEABILITY INDEX OF THE INITIAL STRUCTURE	4.2
SERVICEABILITY INDEX P1 AFTER AN OVERLAY	4.2
MINIMUM OVERLAY THICKNESS (INCHES)	2.0
OVERLAY CONSTRUCTION TIME (HOURS/DAY)	10.0
ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)	1.80
ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)	75.0
WIDTH OF EACH LANE (FEET)	12.0
FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE-MILE)	50.00
ANNUAL INCREMENTAL INCREASE IN MAINTENANCE COST (DOLLARS/LANE-MILE)	20.00

DETOUR DESIGN FOR OVERLAYS
****

TRAFFIC MODEL USED DURING OVERLAYING	3
TOTAL NUMBER OF LANES OF THE FACILITY	4
NUMBER OF OPEN LANES IN RESTRICTED ZONE (OVERLAY DIRECTION)	1
NUMBER OF OPEN LANES IN RESTRICTED ZONE (NON-OVERLAY DIRECTION)	2
DISTANCE TRAFFIC IS SLOWED (OVERLAY DIRECTION) (MILES)	0.50
DISTANCE TRAFFIC IS SLOWED (NON-OVERLAY DIRECTION) (MILES)	0.50
DETOUR DISTANCE AROUND THE OVERLAY ZONE (MILES)	0.0

MATERIALS INFORMATION
****

LAYER	MATERIALS CODE	NAME	COST PER CY	MIN. DEPTH	MAX. DEPTH	SALVAGE, PCT.
1	A	ASPHALTIC CONCRETE	13.00	1.00	8.00	25.00
2	B	CRUSHED LIME STONE	4.00	4.00	20.00	70.00

LAYER	MATERIALS CODE	NAME	ELASTIC MODULUS	POISSON RATIO	TEXAS TRIAXIAL TEST U	T	C
1	A	ASPHALTIC CONCRETE	240000.	0.50	200.0	40.0	0.800
2	B	CRUSHED LIME STONE	150000.	0.50	110.0	15.0	0.400
		SUBGRADE	24000.	0.50	16.0	4.0	0.600

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
2	2	ABC	3210	12	SH360	03/01/72	152	3

BASIC-DESIGNS INFORMATION (ACCURACY:EXCELLENT)

NO	D(1)	D(2)	SCI	DEPTH	LAYER	SIGMA1	SIGMA3	EPSLN1	EPSLN3
1	1.0	4.0	0.323						
				1.0	1	-0.721E 02	-0.781E 02	0.239E-04	-0.137E-04
				1.0	2	-0.728E 02	-0.778E 02	0.317E-04	-0.179E-04
				5.0	2	0.854E 02	-0.252E 02	0.417E-03	-0.689E-03
				5.0	3	-0.747E 01	-0.253E 02	0.417E-03	-0.701E-03
2	2.0	4.0	0.268						
				2.0	1	-0.170E 02	-0.663E 02	0.106E-03	-0.203E-03
				2.0	2	-0.354E 02	-0.665E 02	0.106E-03	-0.206E-03
				6.0	2	0.705E 02	-0.198E 02	0.342E-03	-0.560E-03
				6.0	3	-0.529E 01	-0.200E 02	0.342E-03	-0.575E-03
3	4.0	4.0	0.186						
				4.0	1	0.223E 02	-0.420E 02	0.146E-03	-0.256E-03
				4.0	2	-0.164E 01	-0.422E 02	0.146E-03	-0.260E-03
				8.0	2	0.488E 02	-0.130E 02	0.234E-03	-0.383E-03
				8.0	3	-0.306E 01	-0.132E 02	0.234E-03	-0.399E-03
4	8.0	4.0	0.104						
				8.0	1	0.244E 02	-0.173E 02	0.965E-04	-0.164E-03
				8.0	2	0.894E 01	-0.176E 02	0.965E-04	-0.168E-03
				12.0	2	0.272E 02	-0.684E 01	0.127E-03	-0.214E-03
				12.0	3	-0.136E 01	-0.699E 01	0.127E-03	-0.224E-03
5	16.0	4.0	0.061						
				16.0	1	0.139E 02	-0.530E 01	0.432E-04	-0.765E-04
				16.0	2	0.676E 01	-0.543E 01	0.432E-04	-0.787E-04
				20.0	2	0.121E 02	-0.288E 01	0.540E-04	-0.962E-04
				20.0	3	-0.470E 00	-0.294E 01	0.540E-04	-0.100E-03
6	1.0	8.0	0.172						
				1.0	1	-0.663E 02	-0.793E 02	0.314E-04	-0.502E-04
				1.0	2	-0.708E 02	-0.795E 02	0.343E-04	-0.531E-04
				9.0	2	0.456E 02	-0.119E 02	0.218E-03	-0.357E-03
				9.0	3	-0.268E 01	-0.121E 02	0.218E-03	-0.371E-03
7	2.0	8.0	0.155						
				2.0	1	-0.241E 02	-0.712E 02	0.102E-03	-0.193E-03
				2.0	2	-0.417E 02	-0.713E 02	0.102E-03	-0.195E-03
				10.0	2	0.394E 02	-0.101E 02	0.187E-03	-0.307E-03
				10.0	3	-0.215E 01	-0.103E 02	0.187E-03	-0.321E-03
8	4.0	8.0	0.125						
				4.0	1	0.890E 01	-0.472E 02	0.127E-03	-0.223E-03
				4.0	2	-0.120E 02	-0.474E 02	0.127E-03	-0.227E-03
				12.0	2	0.298E 02	-0.747E 01	0.140E-03	-0.233E-03
				12.0	3	-0.148E 01	-0.764E 01	0.140E-03	-0.245E-03
9	8.0	8.0	0.084						
				8.0	1	0.142E 02	-0.207E 02	0.814E-04	-0.136E-03
				8.0	2	0.131E 01	-0.210E 02	0.814E-04	-0.142E-03
				16.0	2	0.187E 02	-0.455E 01	0.852E-04	-0.147E-03
				16.0	3	-0.816E 00	-0.465E 01	0.852E-04	-0.154E-03

TEXAS HIGHWAY DEPARTMENT
FPS - BISTRO
FLEXIBLE PAVEMENT DESIGN USING LINEAR ELASTICITY

PROB	DIST.	COUNTY	CONT.	SECT.	HIGHWAY	DATE	IPE	PAGE
2	2	ABC	3210	12	SH360	03/01/72	152	8

SUMMARY OF THE BEST DESIGN STRATEGIES
IN ORDER OF INCREASING TOTAL COST

	9	10	11	12	13	14	15
MATERIAL ARRANGEMENT	AB	AB	AB	AB	AB	AB	AB
INIT. CONST. COST	3.57	3.60	3.79	3.61	3.81	3.62	4.00
OVERLAY CONST. COST	1.31	1.26	1.06	1.26	1.06	1.26	1.04
USER COST	0.07	0.07	0.06	0.07	0.06	0.07	0.06
ROUTINE MAINT. COST	0.18	0.17	0.18	0.17	0.18	0.17	0.18
SALVAGE VALUE	-0.69	-0.65	-0.61	-0.62	-0.59	-0.60	-0.58
TOTAL COST	4.44	4.46	4.48	4.50	4.51	4.54	4.69
NUMBER OF LAYERS	2	2	2	2	2	2	2
LAYER DEPTH (INCHES)							
D(1)	4.50	5.50	6.50	6.00	7.00	6.50	8.00
D(2)	17.50	14.50	13.00	13.00	11.50	11.50	10.00
NO.OF PERF.PERIODS	3	3	3	3	3	3	3
PERF. TIME (YEARS)							
T(1)	5.8	5.9	6.2	5.9	6.2	5.9	6.5
T(2)	12.6	12.3	12.9	12.3	13.0	12.4	13.6
T(3)	20.3	20.2	20.5	20.3	20.6	20.3	21.4
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)							
O(1)	3.5	2.5	2.5	2.5	2.5	2.5	2.5
O(2)	2.5	3.5	2.5	3.5	2.5	3.5	2.5
SWELLING CLAY LOSS (SERVICEABILITY)							
SC(1)	0.53	0.54	0.55	0.54	0.56	0.54	0.58
SC(2)	0.33	0.32	0.32	0.32	0.32	0.32	0.32
SC(3)	0.18	0.19	0.18	0.19	0.18	0.19	0.17

THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS 37