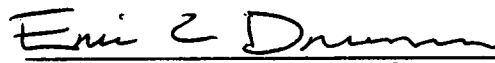
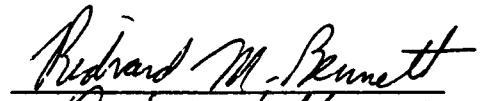


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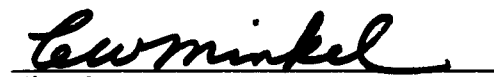
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Eric C. Drumm, Major Professor

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**FINITE ELEMENT APPLICATIONS IN THE ANALYSIS
OF NON-LINEAR PROBLEMS IN GEOMECHANICS**

**A Thesis
Presented for the
Master of Engineering
Degree
The University of Tennessee, Knoxville**

**Jomaa Ben-Hassine
March 1988**

ACKNOWLEDGMENTS

The author would like to thank his major professor, Dr. Eric C. Drumm, very dearly for his continuous guidance throughout the research work required for the completion of this thesis. Special thanks are reserved for Dr. William F. Kane for making his IBM PC-XT available for the PCPAVAN analyses and the writing of this thesis. Thanks are also extended to Dr. Richard M. Bennett and to Dr. Edwin G. Burdette for serving on his committee and to Ms. Elaine Taylor for helping write the equations and produce this document in its final format.

Finally, the author is very grateful to his fiancée, Monia, for providing the very much needed support from across the long, long miles.

ABSTRACT

The analysis of two materially non-linear problems in geomechanics has been performed using a displacement-based two-dimensional finite element formulation.

In the first problem, the stability of residual soils overlaying cavitose bedrock has been investigated. An associative plasticity model has been selected to represent the behavior of the residual soils. Numerous combinations of cavity radius and overburden thickness have been considered. The results have indicated that for thick soil layers, the soil adjacent to the cavity is stable for anticipated cavity radii.

In the second problem, the stress-deformational response of flexible pavement systems has been considered. A linear elastic model has been assumed to represent the behavior of the asphaltic concrete layer. A stress-hardening and a stress-softening model have been used to represent the behavior of the base course and the subgrade, respectively. The effects of layer thicknesses and material parameters have been identified.

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INTRODUCTION

The finite element method (Zienkiewicz, 1977; Dhatt and Touzot, 1984) has been established as a powerful computational tool for solving linear and non-linear, steady-state and transient engineering problems in one, two, and three dimensions. It has gained wide acceptance in most engineering disciplines and has been regarded as the preferred alternative to other well established numerical schemes such as finite difference, collocation, and boundary element schemes.

The finite element method (FEM) is a special case of the method of weighted residuals (MWR) that chooses the weighting functions to be the same as the interpolation functions. Like other methods of numerical solution of differential equations, it transforms the system of differential equations into a set of simultaneous algebraic equations. This is achieved by subdividing the continuum into a number of discrete regions referred to as "finite elements". The differential equation is numerically integrated over every element individually and the resulting algebraic element equations are assembled to form the system matrix. Boundary conditions are applied by simple modifications to the corresponding entries in the system matrix and the right-hand-side vector.

The development of the finite element method is directly linked to the development of digital computers. The computations associated with the solution of the typically large set of assembled system equations requires substantial computational effort. The development of fast and large capacity digital computers has made the application of the method practical and rather attractive. Today, using finite element computer codes to solve problems with complex geometries and non-linear material behavior is standard practice.

There are many different algorithms for solving linear sets of simultaneous equations (Meyer, 1975). These algorithms are rated based on their usage cost, which depends on central processing time as well as use of peripheral devices. Solution algorithms for materially and/or geometrically non-linear problems are usually iterative schemes that require the solution of linear equation sets repeatedly until convergence is achieved (Zienkiewicz, 1977). Therefore, the knowledge gained in developing linear equation solvers is essential to the solution of non-linear problems. Non-linearity in engineering field problems can be classified as either material non-linearity or geometric non-linearity. Material non-linearity is encountered when the system stiffness matrix is dependent on the stress level. Geometric non-linearity, on the hand, is present when small strain theory which assumes a linear strain-deformation relationship is no longer valid due to large strains and/or displacements. However, both types of non-linearity result in a system matrix whose coefficients are not constant; and similar algorithms apply to their solution.

The finite element method has been widely used in the analysis of non-linear problems in geomechanics. However, the main difficulty is encountered in describing the behavior of the non-homogeneous and widely-varying soil materials. Unlike discontinuities in metals which occur at a microscopic level, soil discontinuities occur at a much larger scale, making their effect more pronounced. The formulation of a constitutive model that can adequately describe the behavior of soils is not an easy challenge. Furthermore, soil behavior is so complex that it is impossible to develop a universal constitutive model that can represent all types of soils and all load conditions. Different models for different conditions have been formulated and have resulted in considerable advances (Ko and Sture, 1981). Some models that were developed for metals have been extended to soils. Some other models, such as the capped plasticity models

(DiMaggio and Sandler, 1971), were developed specifically for soil-related problems.

The two applications cited in this thesis deal with material non-linearities only. The first application, stability analysis of residual soils overlaying cavitose bedrock, uses the Sandler cap model which is an incremental associated plasticity model. The second application deals with the structural response of flexible pavement systems and uses nonlinear, stress-dependent behavior models for base and subgrade materials.

Detailed descriptions of the particularities of each of the two applications is found in the next chapters. In particular, the different material models and solution schemes are presented. The results of each application are presented and their implications are discussed. Programming techniques and the use of graphics for pre- and post-processing are presented for both mainframe and microcomputer applications.

Even though the two applications differ significantly in terms of their subject matters, they have many unifying aspects. For instance, they are both materially non-linear problems that require the use of an iterative solution algorithm coupled with an efficient equation solver. In this thesis, these unifying aspects have been emphasized along with the particular aspects of each application.

CHAPTER 1

PRESENTATION OF THE CODE

1.1 GENERAL DESCRIPTION

The Fortran program described herein is a two-dimensional displacement-based finite element code. Originally written at Virginia Polytechnic Institute and State University (Lightner and Desai, 1979; Desai and Lightner, 1985), the code was intended for simulation of construction sequences such as excavations and embankments and for modeling soil-structure interaction. Two-dimensional idealizations of three-dimensional problems, namely, plane strain, plane stress, and axisymmetric idealizations are available. The original code makes available six material behavior models. These models are a linear elastic model, a variable moduli model, a Drucker-Prager plasticity model, a Sandler cap plasticity model, a linear interface model, and a hyperbolic interface model. Also, eight-node isoparametric quadrilateral elements, two-node bar elements, and three-node bar elements are available in the code.

The two finite element applications cited in this thesis make use of the above mentioned code after introducing some changes to make it more suitable for the particular application and the computer being used. These changes are presented in detail in the chapter pertaining to the particular application.

The first of the two applications is a study of the stability of residual soils underlain by cavitose bedrock. This first version of the code, which is named SSTIN, is setup to run on a mainframe computer, namely, the UTCC Vax System.

The second application deals with the analysis of multi-layer flexible pavements. In this application, many analyses have been performed to determine the effect of varying relevant problem parameters on the stress-deformational response of the pavement system. The problem parameters are material related, as reflected in the different material model parameters, and geometry related, as reflected in the different layer thicknesses. The results of these analyses have been used in a parallel study to develop mechanistic flexible pavement design algorithms (Drumm and Moore, 1987). For this second application, the code is adapted to run on a micro-computer system, namely, an IBM PC XT System. This micro-computer version of the code is named PCPAVAN.

In this section, the general structure of the code is described. There are three main phases that make up the code: the data input phase, the solution phase, and the output phase.

1.1.1 Data Input Phase

Data defining the finite element idealization of the problem are read through a formatted input file. The structure of this file is presented in the user's manual. Due to the major differences in the solution schemes and material models used in the two applications presented in this thesis, a separate user's manual is prepared for each application. These different manuals are presented in Appendices D and E.

Some of the special features that speed up the data input task include automatic node and element generation. Automatic node generation is done by specifying the first and last node numbers in a series of nodes that are equidistant and on a straight line; the code internally defines the skipped nodes. Automatic generation of elements is done in a similar fashion; the first and last elements in a pattern are input and the elements between these two ends are

internally generated. As a check of the input data, the mesh is plotted prior to the actual analysis.

In order to make the data input task easier for a person who finds it inconvenient to construct a formatted input file, an input file setup program has been written. This program, the listing of which appears in Appendix 6, is a user-friendly interactive Fortran program that is developed for the flexible pavement version of the code, PCPAVAN.

1.1.2 Solution Phase

Due to the large size of the system matrix for typical problems, most of the computational effort must be allocated to the solution phase. Therefore, the use of an efficient equation solver is an important aspect of cost-efficient codes. The selection of the solver that is most suited for a particular problem depends on the nature of the problem. For finite element models having a chain structure such as beams, the entries in the system matrix tend to be concentrated around the diagonal. For such problems, storing the whole matrix is inefficient; and banded equation solvers are appropriate. However, for models with a high degree of element connectivity, the entries are scattered in the system matrix and frontal equation solvers are appropriate.

To provide greater flexibility, and since both one- and two-dimensional elements are present, the code makes available two equation solvers: a banded matrix solver and a frontal solver. A brief description of this latter solver is presented in Section 1.2.2. These solvers are developed for linear systems; however, they are essential tools for solving non-linear systems since solution algorithms of non-linear systems consist of a number of repeated linear solutions.

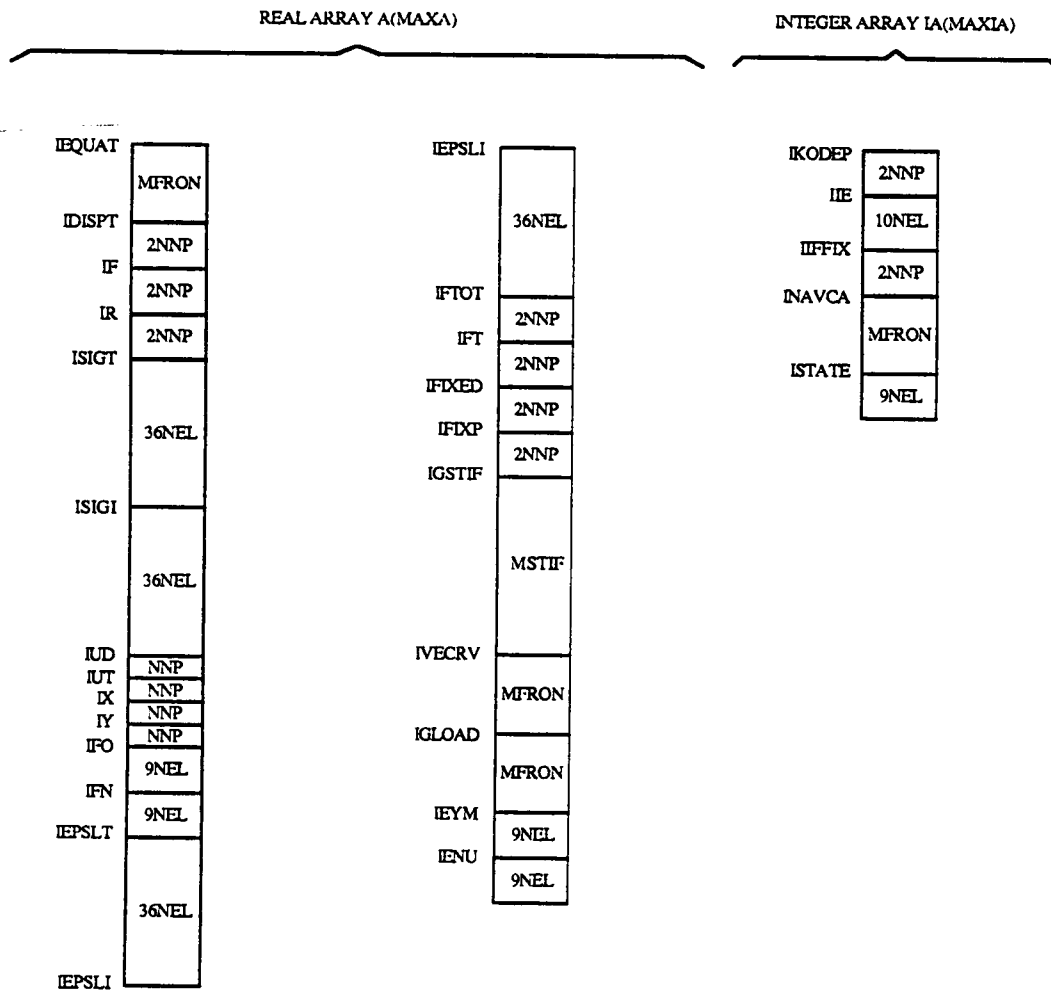
1.1.3 Output Phase

Output consisting of displacements at selected nodes, coordinate stresses, principal stresses, stress invariants and strains evaluated at integration points of selected elements or at selected nodes, and other relevant quantities such as stress states, Young's moduli, and Poisson's ratios are written as output to the screen and to output files. The user can specify the frequency of output for iterations and for load steps. Moreover, in order to facilitate the task of analyzing the results, the mainframe version of the code, SSTIN, uses Calcomp plotting routines to plot displacement vectors, stress states and, the deformed mesh. Post-processing, which includes plotting of relevant response quantities, has been established in most finite element codes as a very important means for gaining a clear idea about the response of the whole system, especially those modeled by a large number of elements.

1.2 SPECIAL FEATURES

1.2.1 Dynamic Dimensioning

In order to facilitate the task of changing the maximum problem size that the code dimensions allow, a form of dynamic dimensioning has been adopted (Hinton and Owen, 1977). Dynamic dimensioning makes it possible to change array sizes necessary for a particular problem by accessing one subroutine only. This task is achieved by defining one variable size array for all real variables and another variable size array for all integer variables. Array pointers are used to separate the different quantities stored in each variable size array. The size of each of these two arrays can be expressed in terms of some problem parameters such as the number of nodal points, the number of elements, and the maximum front width defined in the next section. Figure 1.1 shows how the real and integer quantities are arranged in the variable size arrays for the mainframe version of



NNP = number of nodal points
 NEL = number of elements
 MFRON = maximum front width
 $MSTIF = (MFRON * MFRON - MFRON)/2 + MFRON$
 $MAXA = 180 * NEL + 22 * NNP + 4 * MFRON + (MFRON * MFRON - MFRON)/2$
 $MAXIA = 19 * NEL + 4 * NNP + MFRON$

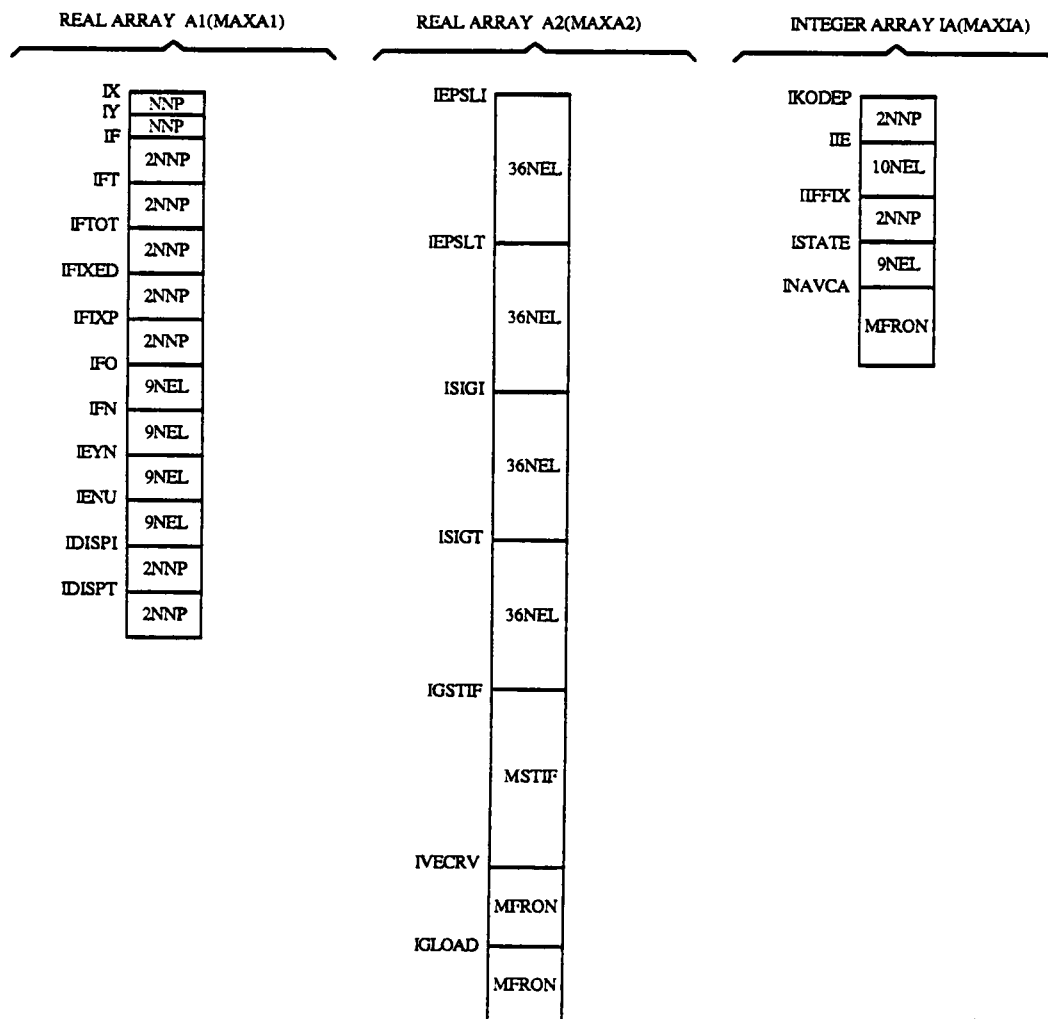
Figure 1.1. Variable Size Arrays used in the General Version of the code SSTIN

the code, SSTIN. For the microcomputer version, PCPAVAN, which is developed solely for the analysis of flexible pavements, the real variable size array is divided into two arrays. This division is made necessary in order to take advantage of the faster math operations available on microcomputers for I2-type integers. Figure 1.2 shows the variable size arrays used in the pavement version of the code.

1.2.2 Frontal Equation Solver

Solving a set of simultaneous linear equations is the step that consumes the greatest portion of the computing time required by most finite element programs. Therefore, the efficiency of the equation solver has a direct impact on the efficiency of the whole code. The ideal equation solver is the one that minimizes total computer cost, which is a function of central processing time and peripheral processor time (Meyer, 1975). A solver that operates wholly in core memory is usually a fast one; however, the available core memory is sometimes inadequate. On the other hand, a solver that makes extensive use of peripheral storage devices to minimize core memory requirements is usually slow due to input-output operations. Therefore, an acceptable trade-off between speed and memory requirements must be achieved.

The frontal solution routine is a solver that minimizes the core memory requirements and central processing time but uses storage devices extensively. This solver was first introduced by Irons (1970) and has been written in modular form and successfully implemented (Hinton and Owen, 1977; Owen and Hinton, 1980). The frontal technique uses a Gaussian elimination and back-substitution process to solve for the unknown variables. Its main feature is that it performs the assembly and elimination steps of the solution simultaneously. The assembly/elimination process is performed on an element-by-element basis. When



NNP = number of nodal points
 NEL = number of elements
 MFRON = maximum front width
 $MSTIF = (MFRON * MFRON - MFRON)/2 + MFRON$
 $MAXA1 = 16 * NNP + 36 * NEL$
 $MAXA2 = 144 * NEL + 3 * MFRON + (MFRON * MFRON - MFRON)/2$
 $MAXIA = 4 * NNP + 19 * NEL + MFRON$

Figure 1.2. Variable Size Arrays used in the PavementVersion of the code PCPAVAN

the contributions of all relevant elements are accounted for at a node, the fully assembled equations associated with the degrees of freedom at that node, along with bookkeeping information that is needed for back-substitution, are transferred to disk storage. The equations that are being assembled at any one time and their corresponding nodes and degrees of freedom are called the front. The number of variables present in these equations is the frontwidth. At any one time during the solution, only the equations containing variables pertaining to the front need to be present in core memory. When all the elements are considered and all the equations assembled and stored, solving for the unknown quantities can be achieved by reading the stored information and back-substituting.

It is worthy to note that even though the frontwidth varies continuously as new nodes are activated, i.e., when they enter the front for the first time, and old nodes are deactivated; i.e., when they appear in the front for the last time, the amount of core memory occupied at any one time can never be greater than that required by a banded solution (Hinton and Owen, 1977). This advantage is of great value for microcomputer applications since core memory is limited. For this reason, the frontal method is the only equation solver available in the microcomputer version, PCPAVAN

From this brief description of the frontal method, it should be noted that while node numbering does not affect core memory requirement, element numbering is critical. Elements should be numbered across the shortest dimension of the model in order to minimize the maximum frontwidth. This is in contrast with banded solvers where element numbering is irrelevant while node numbering is important since it determines the bandwidth.

CHAPTER 2

FIRST APPLICATION: STABILITY ANALYSIS OF RESIDUAL SOIL:

OVERLAYING CAVITOSE BEDROCK IN KARST TERRAIN

2.1 INTRODUCTION

The stability of residual soils overlaying cavitose bedrock should be evaluated prior to the development of storage facilities of environmentally hazardous waste. The site under consideration is the West Chestnut Ridge which is located on the Oak Ridge Reservation, Tennessee. This site has several solution cavities associated with its karst features. Extensive work has been done to characterize the geology and hydrology of the site (Ketelle and Huff, 1984; Woodward-Clyde Consultants, 1984). Uncertainties with respect to the size of the bedrock cavities and the bridging tendencies of the soil prompted an investigation of the residual soil-bedrock cavity system.

Different sinkhole formation and progressive growth mechanisms have been identified for different geological and hydrological conditions (Ogden, 1984). For the West Chestnut Ridge site, the subsidence mechanism (Beck, 1984) appears to be predominant (Drumm, 1987). In this particular mechanism, groundwater flow, which is drawn toward the solution cavities, results in seepage forces in the soil. These seepage forces act with the gravitational forces and cause displacement of the residual soil by spalling and/or piping. The stresses induced by the loss of support due to the created void are taken up by soil arching above the cavity.

Due to the complexity of the problem, some simplifying assumptions have been made. The effects of neighboring solution cavities on the stability of the

considered residual soil-bedrock cavity system have been neglected. Seepage forces have been neglected and the gravitational forces are the only forces considered. The bedrock cavity is assumed to have a circular cross section and an axisymmetric idealization of the three-dimensional problem has been adopted. Figure 2.1 illustrates the idealization of the complex-real-life problem and Figure 2.2 shows a typical finite element model of the idealized residual soil-bedrock cavity problem.

The stability of the idealized residual soil-bedrock cavity system can be expected to be a function of the cavity size, the thickness of the overburden, and the properties of the residual soil. Hence, in order to obtain a general idea about how these factors interact and how much each affects the stability of the system, a series of axisymmetric analyses have been performed using different combinations of variables over a reasonable range of their variations. The results are presented in the form of normalized curves that can serve as a useful guide for the qualitative evaluation of the stability of a given soil-bedrock cavity system.

2.2 MATERIAL MODEL

The formation and progressive growth of sinkholes can be attributed to many factors most of which are geology and hydrology related. In this work, however, another important aspect, namely the structural aspect, is considered. It is assumed that the effect of all the other factors such as geology, as reflected by the kind of soil, and hydrology, as reflected by the water content, can be represented by a single soil behavior model. It is very hard, if not impossible, to devise a practical behavior model that can represent all of the interacting factors that are present in a soil mass of a certain type, located a certain distance from the water table, and having a certain loading history. With all of these factors

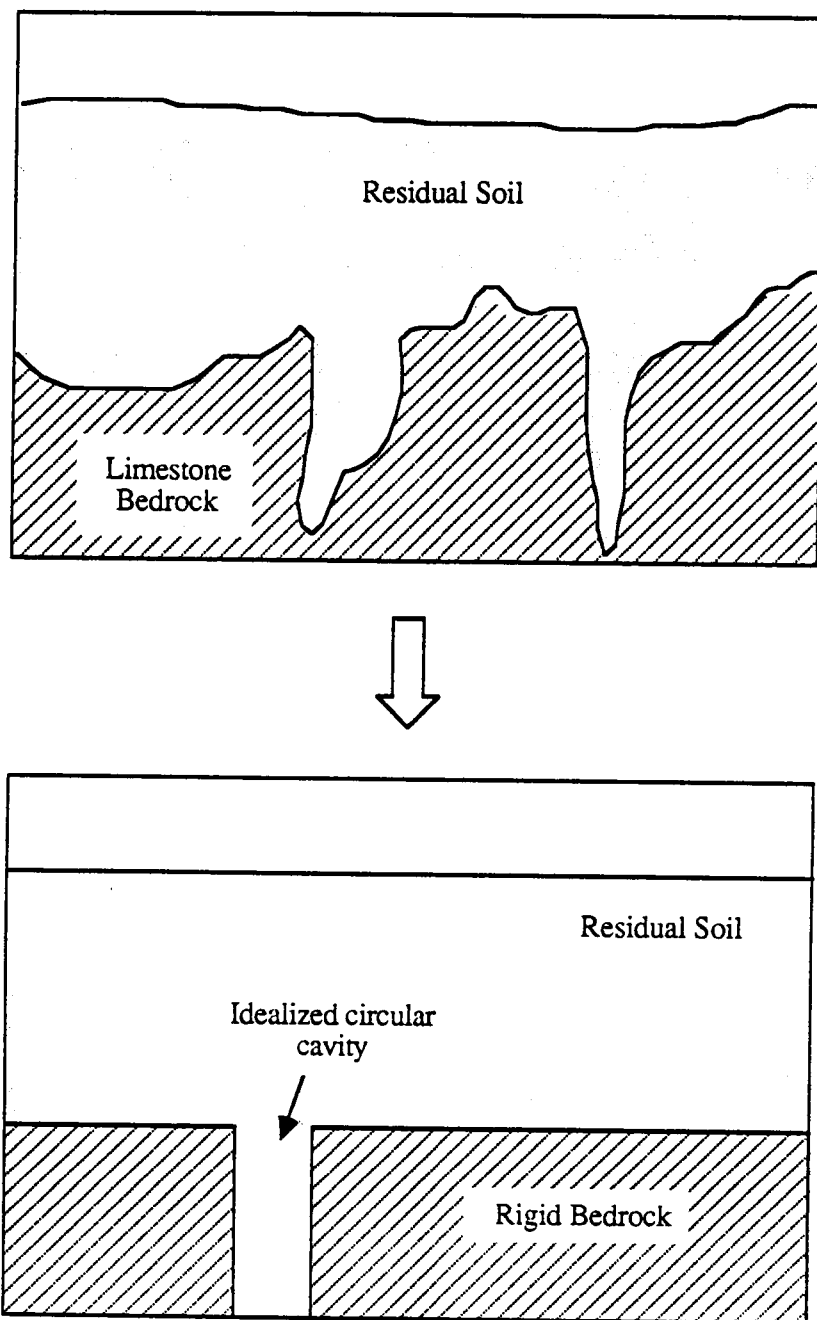


Figure 2.1. Idealization of the Residual Soil-Bedrock Cavity Problem

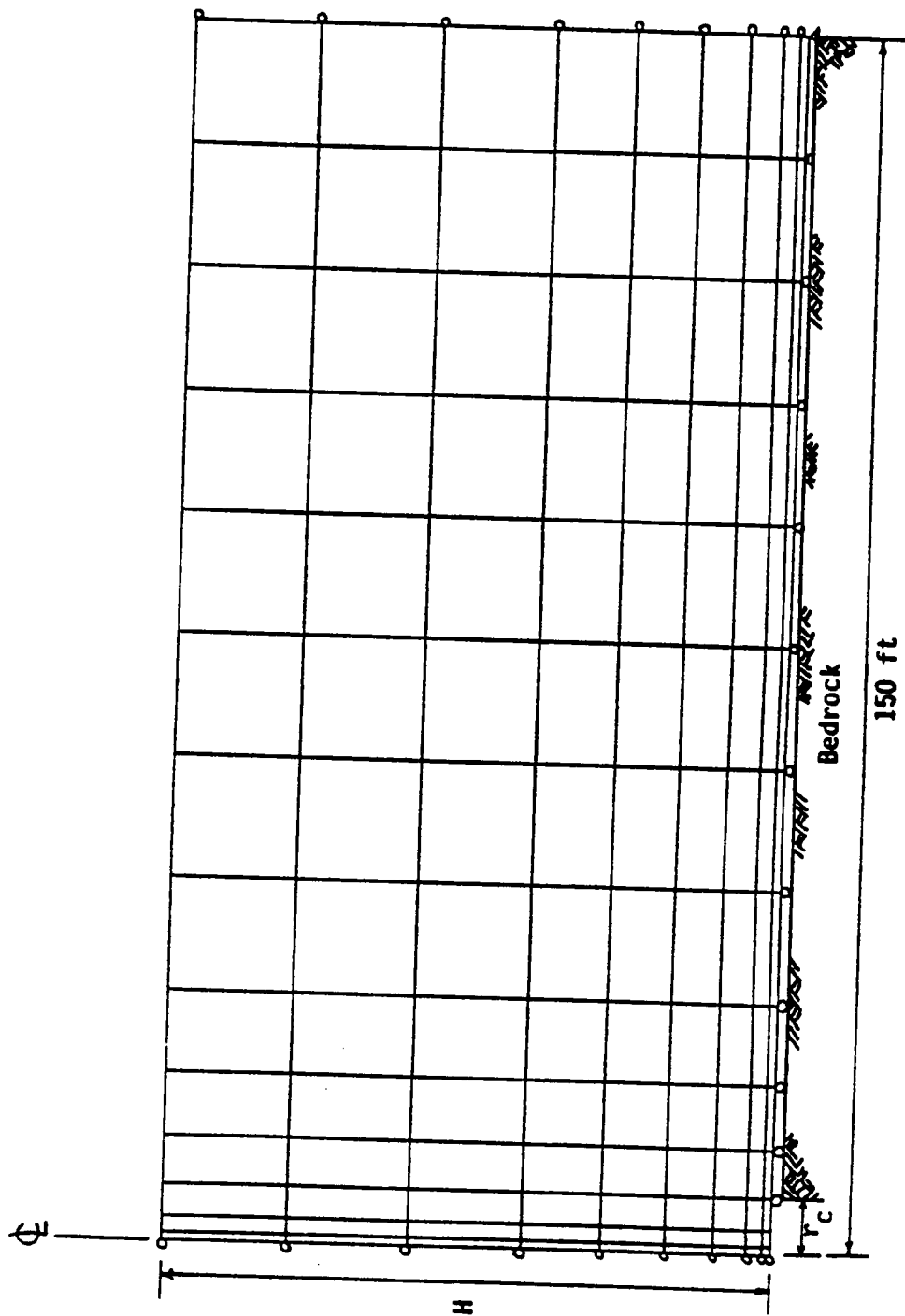


Figure 2.2. Typical Finite Element Model of the Idealized Residual Soil-Bedrock Cavity System

interacting simultaneously, there is no reason to expect the deformation of such a soil mass to be proportional to the load acting on it. In other words, linearity of the stress-strain relationship is not guaranteed. Furthermore, upon removal of the load, the soil mass does not regain its original shape, indicating that a part of the strain is not recovered. Thus, elasticity is not guaranteed either. The behavior is then far from being linear elastic and a linear elastic constitutive relation cannot represent it properly.

Although there are many incremental elasto-plastic constitutive models that are applicable to soils (Ko and Sture, 1981; Chen, 1983), the Sandler cap model (Sandler et al., 1976) is found to adequately represent the behavior of the residual soil existing at the site under consideration. The main advantages of this model over other models are its ability to represent plastic strain hardening, unloading behavior, and general material response under a variety of stress paths, while being relatively simple and requiring relatively few material parameters. A brief description of the Sandler cap model is now presented; for a more detailed description, consult the cited references (Sandler, DiMaggio, and Baladi, 1976, Sandler and Rubin, 1976, and 1979).

The Sandler cap model is an incremental, associated plasticity constitutive model. In incremental plasticity, it is assumed that the incremental strain tensor can be divided into an incremental elastic strain tensor $d\epsilon_{ij}^e$ and an incremental plastic strain tensor $d\epsilon_{ij}^p$; i.e.,

$$d\epsilon_{ij} = d\epsilon_{ij}^e + d\epsilon_{ij}^p \quad (2.1)$$

In associated plasticity, the plastic potential function which determines the plastic strain increment is assumed to be the same as the yield function which defines the stress state that limits elastic behavior. The resulting flow rule, also called the normality rule, is said to be associative and is expressed as

$$d\epsilon_{ij}^p = \lambda \frac{\partial F}{\partial \sigma_{ij}} \quad (2.2)$$

where $d\epsilon_{ij}^p$ is the incremental plastic strain tensor, σ_{ij} is the stress tensor, F is the yield function, and λ is a scalar multiplier.

The yield function for the Sandler cap model is formulated in the J_1 - $\sqrt{J_{2D}}$ space, where J_1 is the first invariant of the stress tensor expressed as

$$J_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \quad (2.3)$$

and $\sqrt{J_{2D}}$ is the square root of the second invariant of the deviatoric stress tensor expressed as

$$\sqrt{J_{2D}} = \left\{ \frac{1}{6} \left[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 \right] \right\}^{\frac{1}{2}} \quad (2.4)$$

The Sandler cap yield function is symmetric about the hydrostatic $\sqrt{J_1}$ axis and consists of two parts (Figure 2.3):

1. A fixed plastic failure envelope which depends on the state of stress only.

It is described by

$$\sqrt{J_{2D}} = F_1(J_1) = A - C e^{BJ_1} \quad (2.5)$$

2. A moving hardening cap function that depends on the state of stress as well as the current value of the hardening parameter k . The moving cap has the form of an ellipse with aspect ratio R , and is described by

$$\sqrt{J_{2D}} = F_2(J_1, k) = \frac{1}{R} \left[\left(X(k) - L(k) \right)^2 - \left(J_1 - L(k) \right)^2 \right]^{\frac{1}{2}} \quad (2.6)$$

where k is related to the volumetric plastic strain by

$$\bar{\epsilon}_v^p = W \left(e^{DX(k)} - 1 \right) \quad (2.7)$$

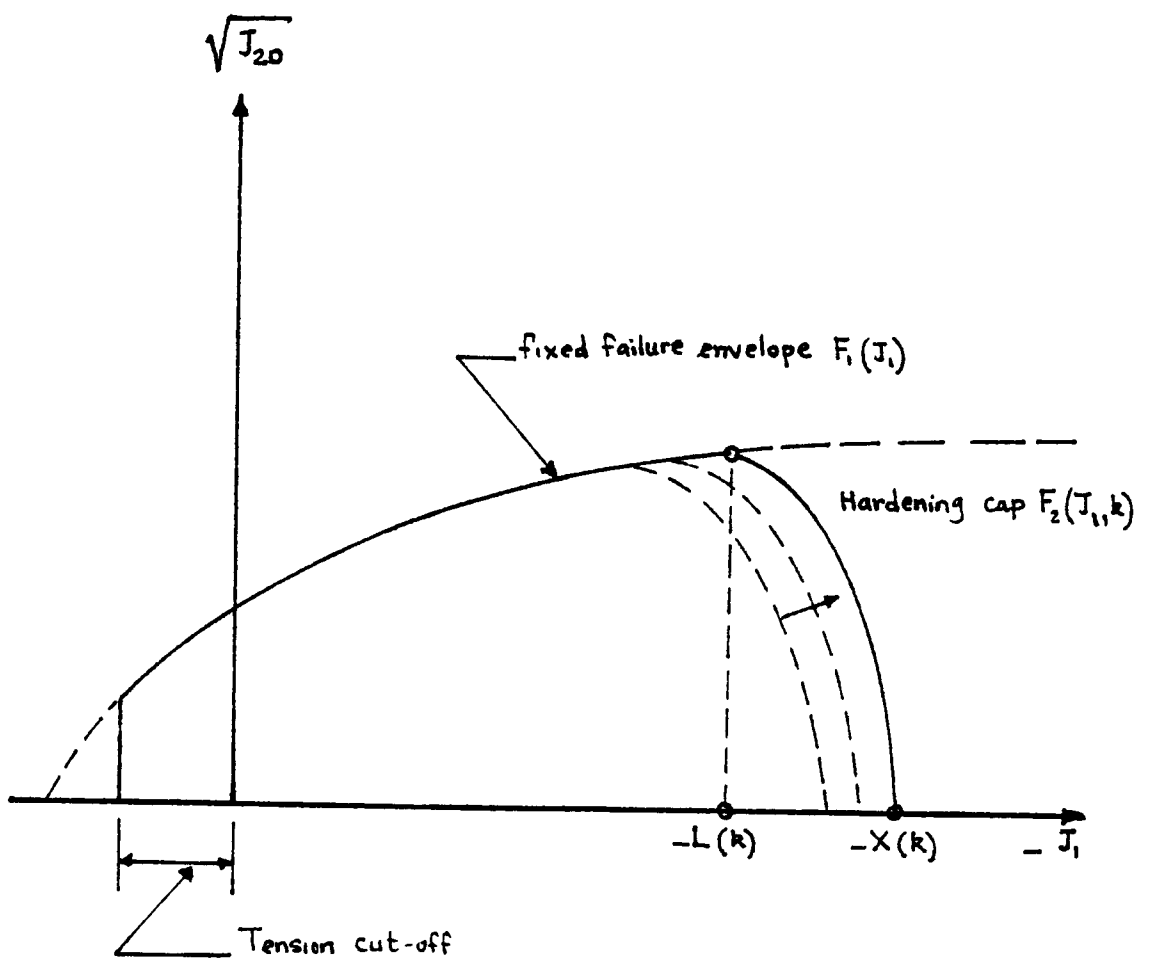


Figure 2.3. Sandler Cap Model

and $L(k)$ and $X(k)$ determine the location of the cap on the J_1 axis. They are expressed by

$$L(k) = \begin{cases} k & \text{for } k < 0 \\ 0 & \text{for } k \geq 0 \end{cases} \quad (2.8)$$

and

$$X(k) = k - R F_1(k) \quad (2.9)$$

In the equations above, A , B , C , D , R and W are experimentally determined material parameters.

The Sandler cap model can represent three modes of behavior: an elastic mode which can be in compression or in tension with a specified tension cut-off value, a failure, or ultimate, mode if the stress state reaches the fixed failure envelope, and a cap, or strain hardening, mode when the stresses are on the moving cap.

Typically, conventional tests such as triaxial compression, hydrostatic compression, and uniaxial strain are used to determine the material model parameters. Then, the resulting model is used to back-predict the laboratory data to check its validity. The model should also be tested in a variety of stress paths to check if they are all adequately represented. However, the only laboratory data available for the considered site consisted of consolidated undrained triaxial compression tests (Woodward-Clyde Consultants, 1984). From these tests, parameters A , B , and C have been determined, and, due to the lack of the hydrostatic test data, parameters D , W , and R have been approximated (Drumm, E. C., 1987). The material parameters used in all the residual soil-bedrock cavity analyses are summarized in Table 2.1.

2.3 SOLUTION SCHEME

Numerical processes for the solution of non-linear problems are very well documented in the literature (Owen and Hinton, 1980). Discretization of the

**Table 2.1. Summary of Sandler Cap Model Parameters
Used in the Residual Soil-Bedrock Cavity Analyses**

Parameter	Value	Unit
E	2100	Ksf
ν	0.45	—
γ	120	psf
A	4.0	Ksf
B	0.10	Ksf ⁻¹
C	3.50	Ksf
D	0.035	Ksf ⁻¹
W	0.2	—
R	2.0	—

continuum into finite elements yields a set of simultaneous equations that can be solved using any of the many equation solvers available. However, in the case of non-linear problems, the coefficients are not constant; rather, they depend on the values of the variables found in the solution. The solution of this system of equations can no longer be arrived at directly. An iterative scheme that is appropriate for the particular problem must be used. These schemes take advantage of the established methods of solving linear equation sets by applying them repeatedly until achieving convergence. A large variety of schemes exist, however, they can be classified as incremental, iterative, or mixed schemes. In incremental schemes, the total load is applied in small load increments without any corrections for the non-linear material behavior at the end of each load step. In iterative schemes, the total load is applied in one step and iterations are performed to account for the non-linear behavior. The solution scheme used for the residual soil-bedrock cavity system is a mixed one: the applied load is divided into load steps and iterations are performed over every step.

The Newton-Raphson iterative solution algorithm (Owen and Hinton, 1980; Zienkiewicz, 1977) is chosen. This scheme is based on minimizing the residual forces in the system. At the start of a load step, nodal forces equivalent to the load increment are applied, and the response of the system is evaluated using the stiffness obtained after convergence of the previous load step. Using the resulting stresses, the coefficients of the equivalent elasto-plastic stiffness matrix are determined based on the Sandler cap model formulation. The equilibrium nodal loads are then determined. Using the new stiffness, the difference between the applied loads and the equilibrium loads are the residual forces which are applied as loads during the next iteration. The same procedure is repeated until the residual forces are very small. A global convergence check is performed by evaluating the norm of residual forces over all nodal points and dividing it by the

norm of the initial nodal loads; if this ratio is less or equal to 0.01 then convergence is achieved. This convergence check has wide acceptance (Owen and Hinton, 1980) and can be expressed as:

$$\frac{\sqrt{\sum_{i=1}^n (\psi_i^r)^2}}{\sqrt{\sum_{i=1}^n (f_i)^2}} \leq 0.01 \quad (2.10)$$

where $\sqrt{\sum_{i=1}^n (\psi_i^r)^2}$ is a norm based on the residual forces at iteration number r , $\sqrt{\sum_{i=1}^n (f_i)^2}$ is a norm based on the applied nodal forces, and n is the number of nodes.

Figure 2.4 shows a block diagram of the solution scheme of the residual soil-bedrock cavity problem, and Figure 2.5 is an illustration of the Newton-Raphson iterative method.

2.4 RESULTS AND DISCUSSIONS

Failure in subsidence dolines is progressive; i.e., as long as the hydrological conditions are favorable, the system is increasingly distressed until reaching collapse. To prevent collapse or excessive damage, intervention to alter the drainage conditions is necessary. However, this study is not concerned with that aspect of the problem; rather, its purpose is to qualitatively evaluate the structural response of an idealized residual soil-bedrock cavity system for a given set of geometric and loading conditions. Three parameters have been varied and their effects on the level of distress in the system have been investigated. These parameters are the radius of the bedrock solution cavity, the thickness of the overburden, and the value of structural surcharge. The values used for the different combinations of these parameters are presented in Table 2.2. Cavity radius and overburden thickness values represent the range of variation at the considered site (Ketelle and Huff, 1984).

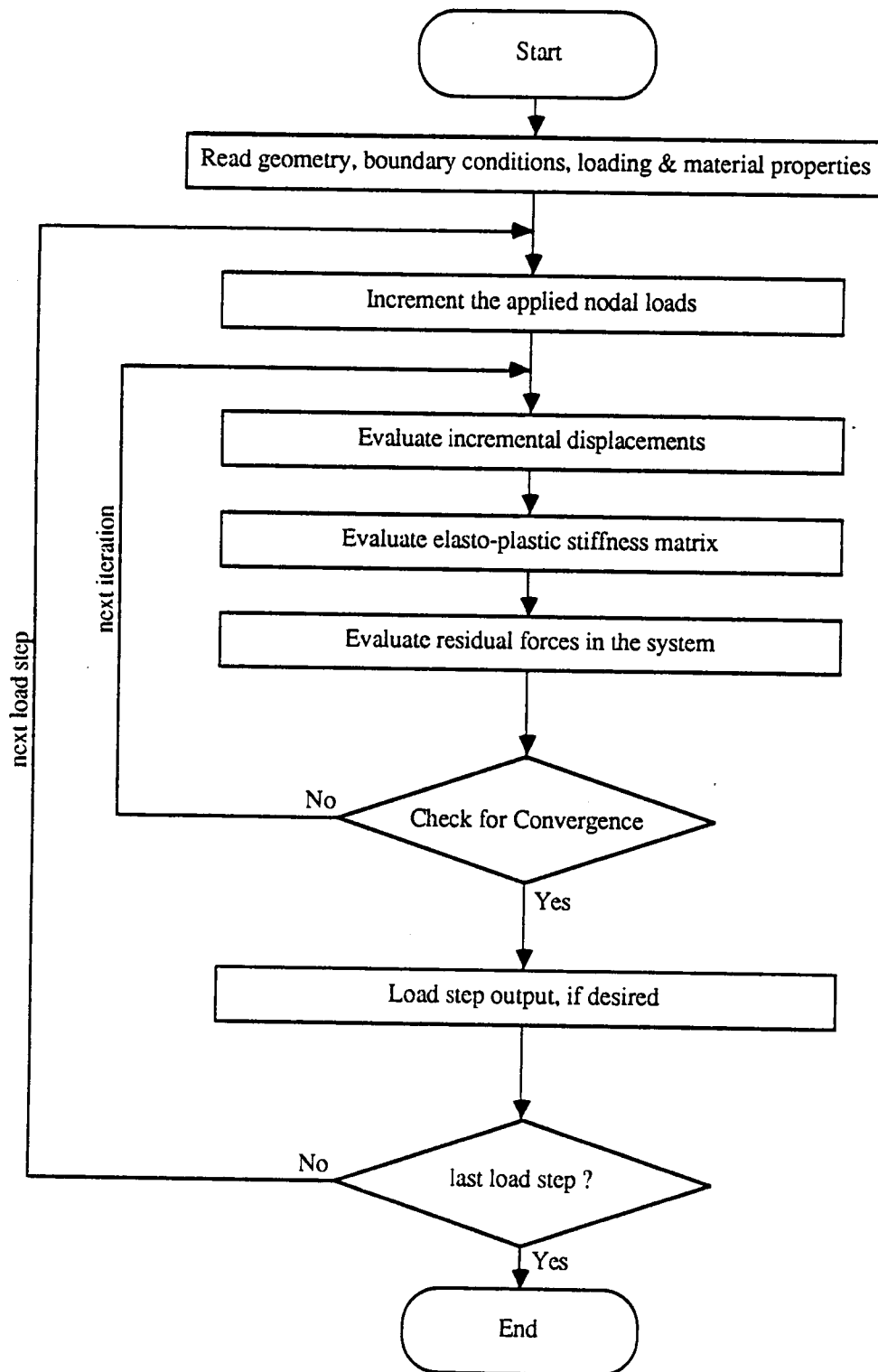


Figure 2.4. Flowchart of the Solution Scheme for the Residual Soil-Bedrock Cavity System

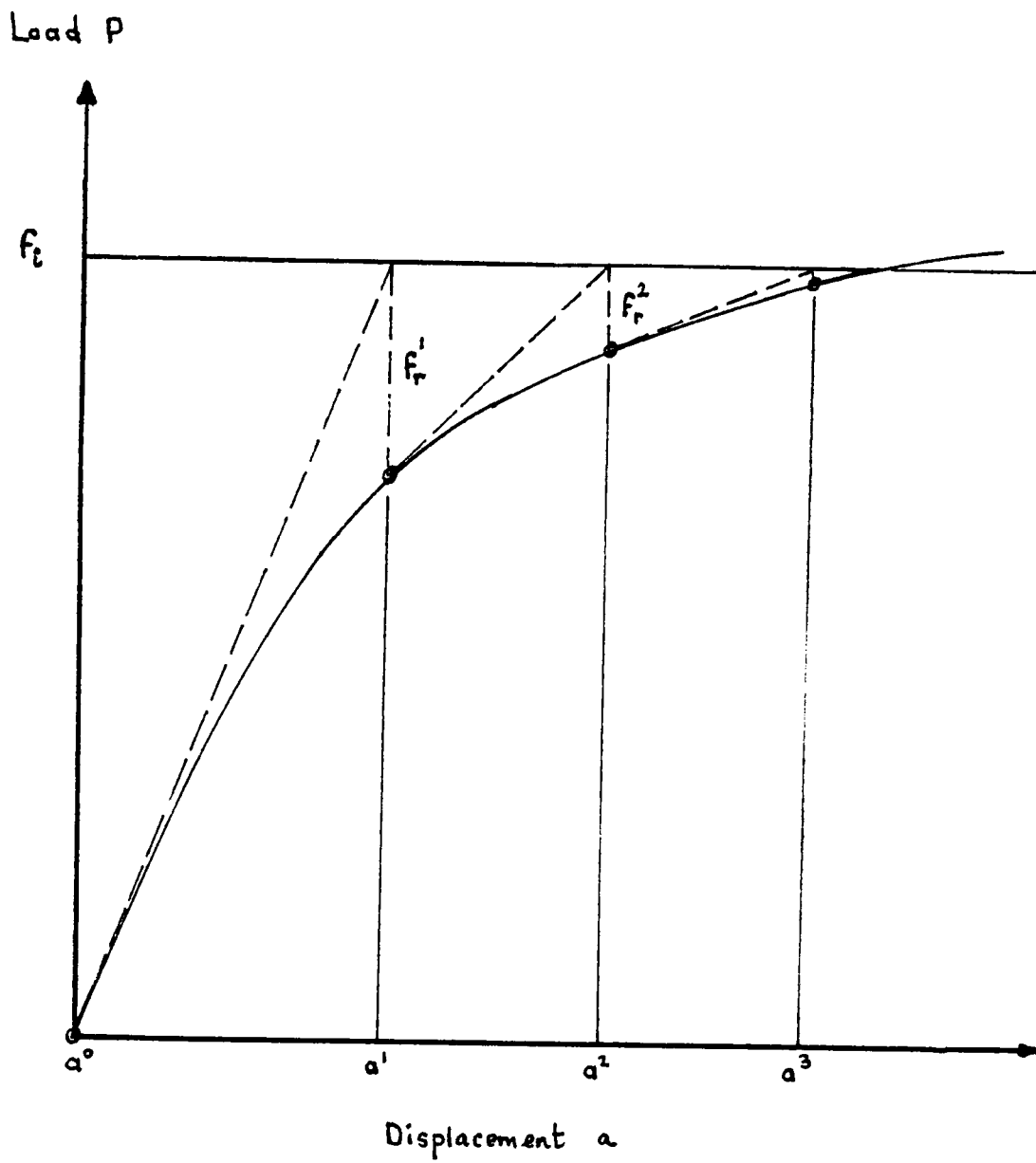


Figure 2.5. Newton-Raphson Iterative Method

Table 2.2. Summary of Bedrock Cavity-Residual Soil Analyses

Overburden Thickness (ft)	Cavity Radius (ft)	Surface Surcharge (ksf)
30	0.5,1.0,3.0,7.0,10.0,13.0	0.0,1.0
75	0.5,1.0,3.0,7.0,13.0	0.0,1.0
150	1.0,2.0,6.0,10.0,14.0,26.0	0.0

Starting with a stress-free field, the insitu loading is applied incrementally; and the resulting stresses evaluated at every step according to the constitutive model. The Sandler cap model, which is chosen to represent the behavior of the residual soil at the site, allows for the classification of the stress state at every integration point as either elastic compression, elastic tension, hardening cap or plastic failure. When the stress state is elastic, the material can take more load safely. A cap stress state signifies that although the material is yielding, it is still capable of carrying more load due to hardening. Part of the strain is plastic and is therefore irrecoverable. Finally, when the stress state is fully plastic, the material has reached its ultimate strength and is not providing any support.

Stress states are evaluated at four integration points per element. Therefore, in order to graphically display the analysis results, a decision procedure for declaring the element stress state has been adopted. If any of the integration points has a plastic stress state then the whole element is assumed to have failed and is shaded at a 45 degree angle. If there are no plastic stress states, the integration points are checked for tension stress states and the element shaded at a 135 degree angle if there are any tension integration points. If there are no plastic or tension integration points and cap stress states exist, the element is not shaded. Finally, if all the integration points are elastic, the element is shaded vertically.

From the resulting plot of stress state distribution, the area of the yielded soil, A_y , has been determined and used as a measure of damage. Moreover, since material failure starts around the cavity and migrates up as the load is increased, the maximum height of the plastic region, h_y , which is measured from the bedrock level to the highest plastic integration point has been used as a measure of the extent of damage. The area of yielded soil and the maximum height of yielded soil are plotted versus the radius of the bedrock cavity, r_c , in Figures 2.6

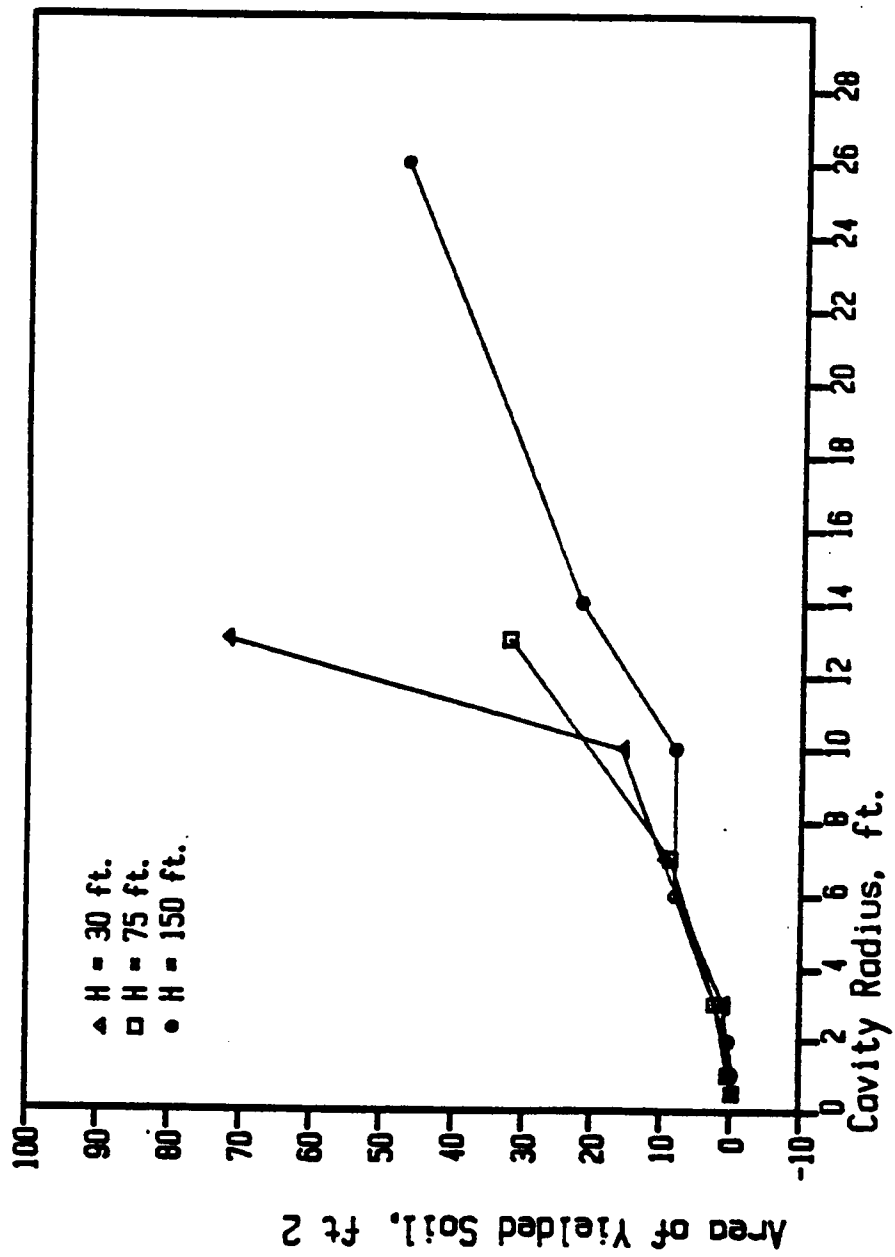


Figure 2.6 Area of Yielded Soil vs Cavity Radius

and 2.7, respectively. However, since the thickness of the overburden, H , is expected to affect the response of the system, cavity radius values have been normalized with respect to overburden thickness. The maximum height of yielded soil, h_y , has been plotted, in Figure 2.8, versus normalized cavity radius for the three overburden thicknesses considered. The scatter in the plotted data can be attributed to the procedure adopted in shading the elements. For instance, an element that has only one of its lower integration points as plastic is assumed to have failed and its whole area is counted in A_y .

From these plots, it is noted that, as intuitively expected, the area of yielded soil and its maximum height are greater for a greater cavity radius. From the normalized plots, it is noted that for low r_c/H ratios, the extent of damage is relatively insensitive to the cavity radius. In other words, for a given overburden thickness, there exists some critical cavity radius value below which the extent of damage is almost constant. When the overburden thickness is high, the critical cavity can have a sizable radius. This result can be attributed to soil arching effects which are greater for thick overburden.

The normalized plots can be used as a useful guide for the evaluation of the extent of damage in terms of the area of yielded soil or its height for a particular combination of cavity radius and overburden thickness. The extent of damage is a strong indicator of how stable the system is. However, it should be noted that hydrological effects are also of critical importance to the stability of the system. Therefore they should be taken into consideration along with the structural aspect studied here.

The deformational response of the system has been shown by plotting, in Figure 2.9, the surface subsidence versus the radial distance from the cavity center for different cavity radii for a 30 foot thick overburden. The predicted surface subsidence is smaller than what is actually observed for karst terrain.

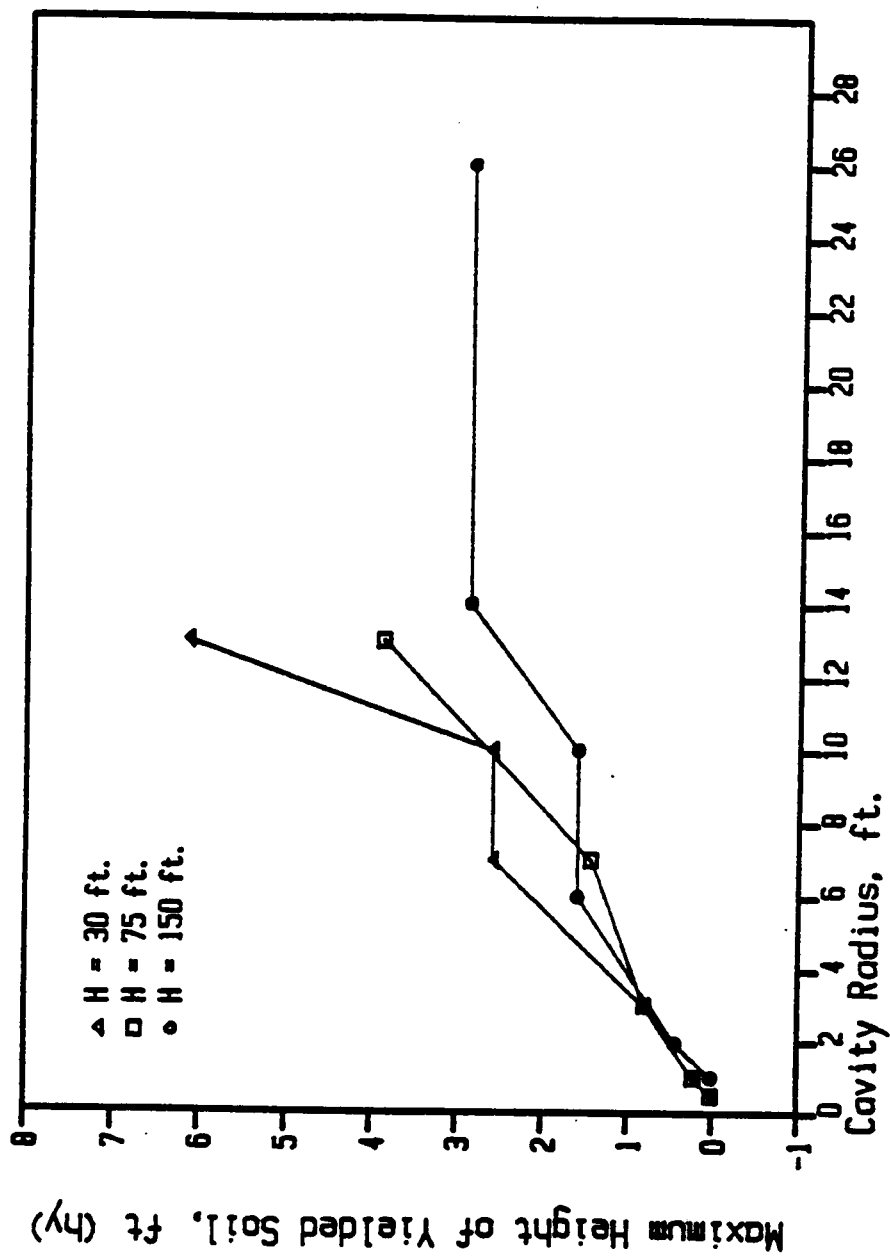


Figure 2.7 Height of Yielded Soil vs Cavity Radius

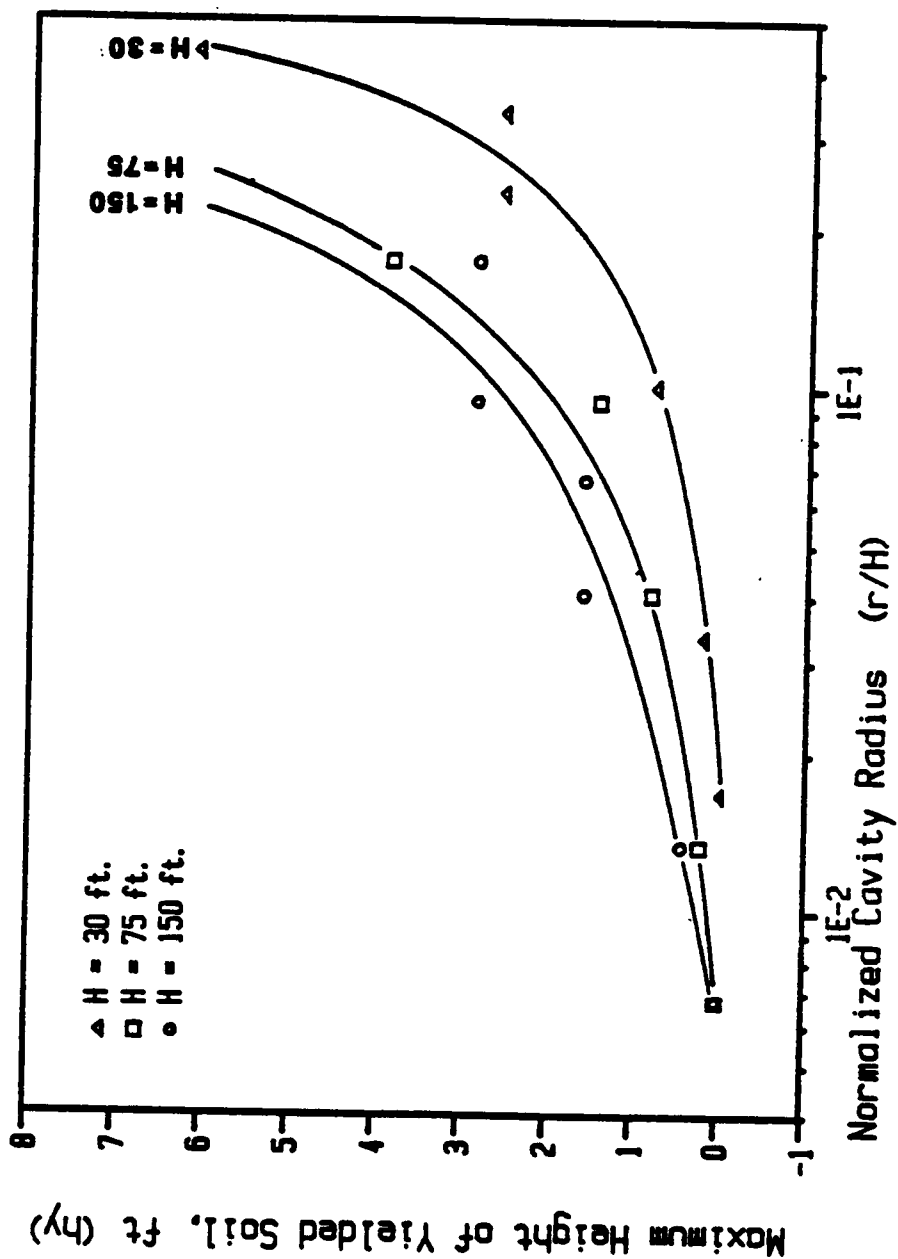


Figure 2.8 Height of Yielded Soil vs Normalized Cavity Radius

SURFACE SUBSIDENCE FOR H=30ft.

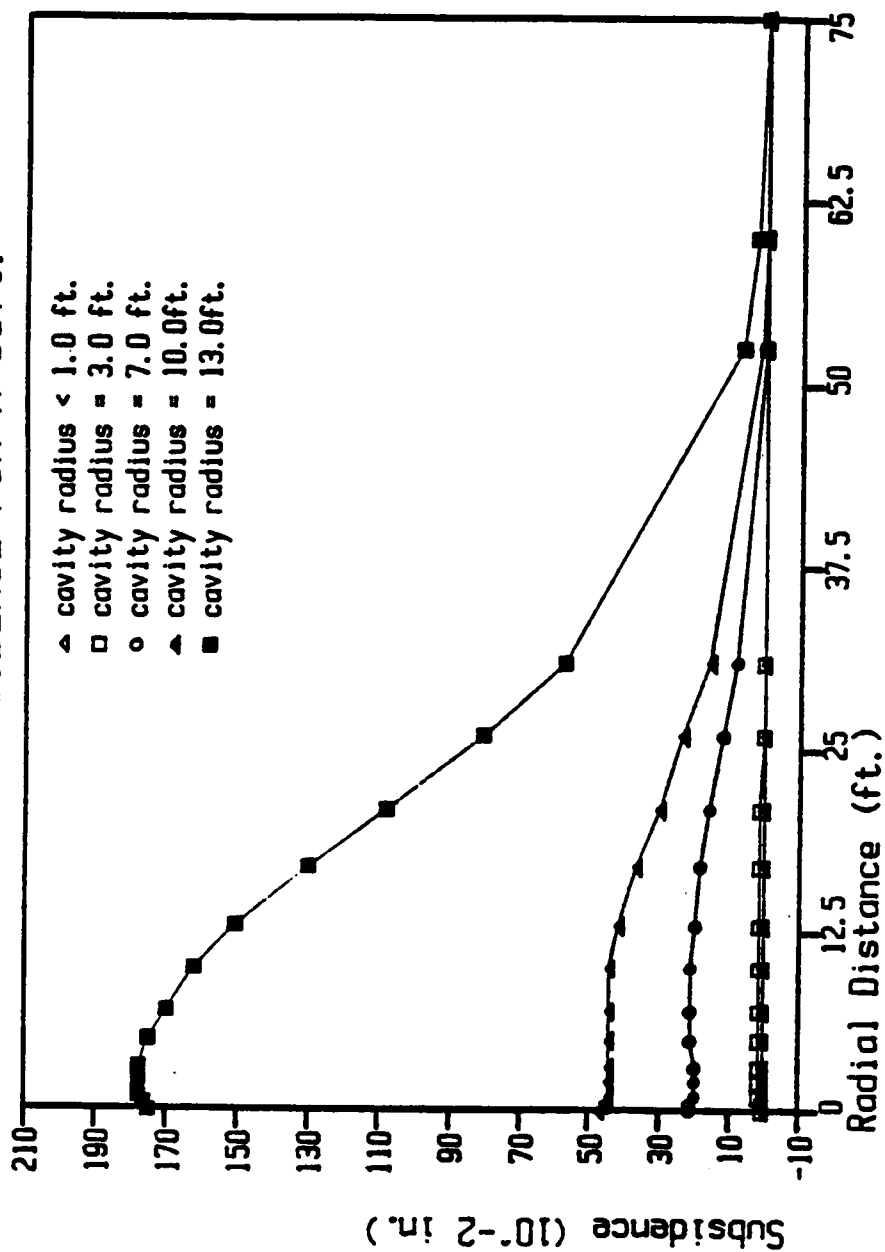


Figure 2.9 Surface Subsidence for a 30 Foot Thick Overburden

This can be explained by inaccurate elastic properties used in the analyses and by neglecting hydrological effects which are predominant in karst terrain.

2.5 PROGRAM ENHANCEMENTS

2.5.1 Switching to Double Precision Arithmetic

The original code was written on a Control Data Corporation (CDC) mainframe computer which is different than the VAX computer available at The University of Tennessee Computing Center. Therefore, some minor machine-related changes had to be made in order for the code to run. The major modification, however, is related to different word lengths used by the two machines. Since the word length used by the original computer is twice that used by the VAX, it was not necessary to use double precision arithmetics in order to minimize truncation errors. However, using single precision arithmetics on the VAX system was not adequate and resulted in precision related instabilities. This problem was remedied by switching to double precision arithmetics. Declaring all real variables as REAL*8 variables resulted in a relatively faster convergence and a reduction in solution instabilities.

2.5.2 Addition of Graphics

Post-processing is considered to be an important feature in almost any finite element code because it is much easier to interpret a plot than it is to interpret a table of numbers. Moreover, plots exhibiting the obtained results can give the interpreter a clear understanding of the response of the system as a whole, not just of a particular element or node. For these reasons, a comprehensive graphics package that utilizes Calcomp plotting routines has been added to the code.

A plot of the original finite element model can be obtained prior to the actual problem solution; thus, the user can check the input data for possible errors in

node numbering or element connectivity before wasting expensive computer time. Figure 2.10 shows a typical plot of a finite element mesh.

The deformational response of the system is presented by plotting the displacement vectors and/or the deformed mesh. Displacement vectors have their tails at the original positions of the nodes and their heads at the final positions. They are plotted at corner nodes only in order to promote clarity in finely discretized regions. A deformed mesh is obtained by connecting the displaced nodes. The displacements used to plot the vectors and the deformed mesh are multiplied by a user-selected magnification factor in order to show the system response more clearly. Figures 2.11 and 2.12 show typical plots of displacement vectors and deformed mesh, respectively.

There are many commonly used techniques of presenting the variation of stress throughout the discretized continuum. They include contour lines and plots of principal stresses and their orientations. The technique used in this work is a qualitative one that provides an insight about the stress distribution. The constitutive model used for the analysis, Sandler cap model, makes it possible to classify the stress state at an integration point as elastic, cap, plastic, or tension. This information is used to shade an element differently depending on the stress state of most of its integration points. The resulting shaded mesh provides indications about the failed "plastic" regions, the yielding "capped" regions and the "elastic" regions. Thus, an important objective of this study, namely the extent of soil yielding around the cavity, is graphically presented. Figure 2.13 shows a typical plot of stress state distribution.

It should be noted that limiters on load steps for any of these plots are specified by the user. Therefore, the gradual response of the system as the load is being incremented can be observed at desired load intervals.

JOB # 19	FINITE ELEMENT MESH		ICR # 2
HEIGHT (FT)	=30.0	NO. OF ELEMENTS	=54
WIDTH (FT)	=75.0	NBAND OR MFRON	=46
NO. OF NODAL PTS	=193	SCALE	= (1/100) X 9.333

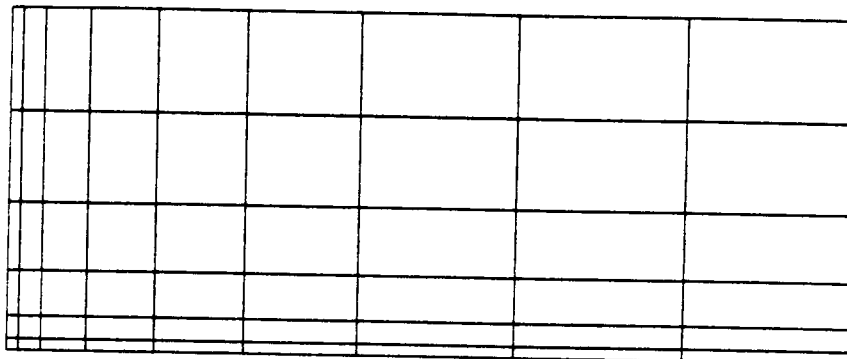


Figure 2.10. Typical Plot of Finite Element Mesh

JOB # 5	DISPLACEMENT VECTORS	100 % OF LOAD
MAGNIFICATION =4.		

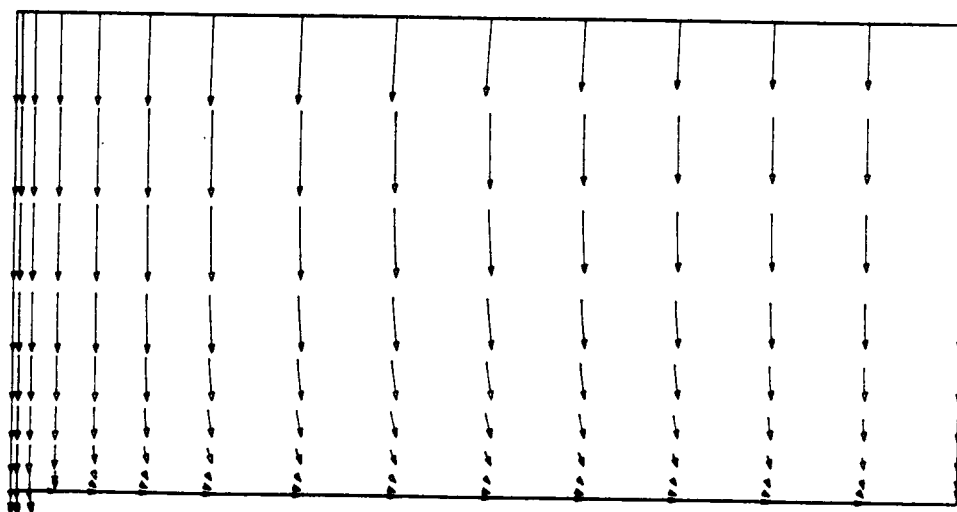


Figure 2.11. Typical Plot of Displacement Vectors

JOB # 5	DEFORMED MESH	100 % OF LOAD
MAGNIFICATION =4.		

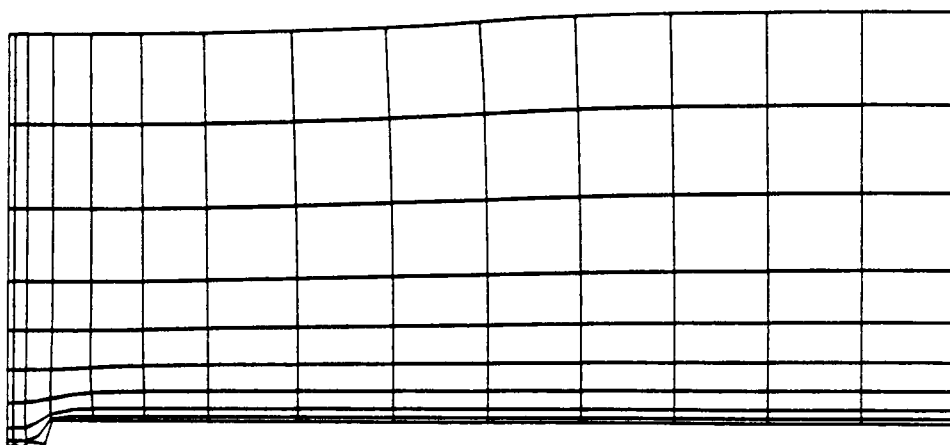


Figure 2.12. Typical Plot of Deformed Mesh

JOB # 5	STRESS STATES DISTR.	100 % OF LOAD
 PLASTIC	 ELASTIC	
 TENSION	 CAP	

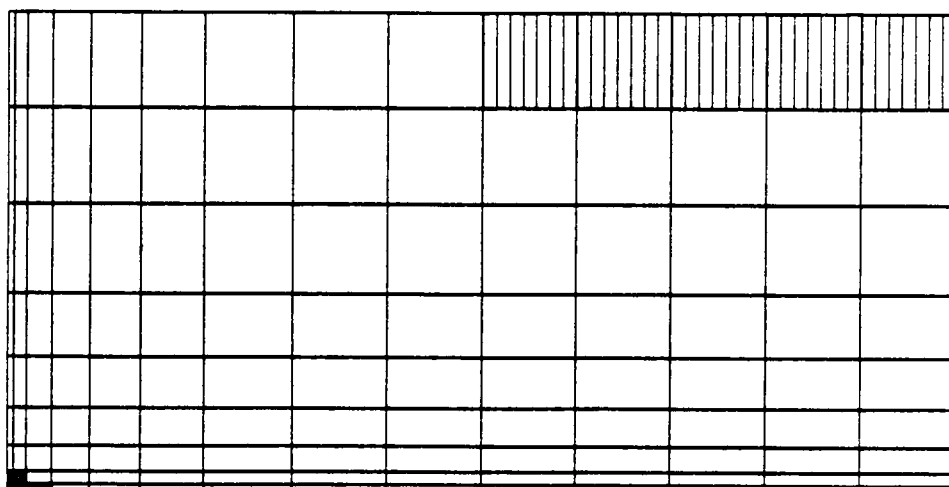


Figure 2.13. Typical Plot of Stress State Distribution

CHAPTER 3

SECOND APPLICATION: ANALYSIS OF FLEXIBLE PAVEMENTS

3.1 INTRODUCTION

In the second application of the finite element method, the response of flexible pavements to cyclic traffic loads is considered. As in the first application, the results of a series of analyses involving many combinations of variables are used to formulate simple design algorithms. Asphaltic concrete (AC) thicknesses of 3, 6, 10 and 18 inches and base course thicknesses of 4, 6 and, 10 inches have been considered. Material properties for AC, base, and subgrade layers are presented in Table 3.1. In order to account for temperature effects, four sets of AC elastic properties have been considered. Four types of subgrades, namely, stiff, medium, soft, and very soft subgrades have been considered in order to cover the wide variation in subgrade materials. Only one characterization for the gravel base course has been included in the analyses.

This work is very similar to previous work (Elliot and Thompson, 1984) in its scope and procedure. However, the finite element formulation used in this work should yield better results since the eight-node isoparametric quadrilateral element used is of higher order than the constant strain triangle used by other investigators.

The pavement system is modeled by a series of layers representing the different materials. An axisymmetric model is selected with an 80 psi traffic load applied uniformly on a six inch radius circular area at the centerline of the

Table 3.1. Summary of Material Properties of Flexible Pavement Analyses

ASPHALTIC CONCRETE				
	A	B	C	D
Young's Modulus (Ksi)	100.0	500.0	1000.0	1500.0
Poisson's Ratio	0.460	0.400	0.325	0.250
GRAVEL BASE				
Poisson's Ratio	0.38			
K	4000.0			
n	0.50			
ϕ (Degrees)	30.0			
c (psi)	0.0			
SUBGRADE MATERIALS				
	Stiff	Medium	Soft	Very Soft
Poisson's Ration	0.45	0.45	0.45	0.45
E _{ri} (ksi)	12.34	7.68	3.02	1.00
K ₁ (ksi/psi)	-1.11	-1.11	-1.11	-1.11
K ₂ (ksi/psi)	-0.178	-0.178	-0.178	-0.178
Deviator Stress @ breakpoint (psi)	6.20	6.20	6.20	6.20
Deviator Stress Upper Limit (psi)	32.80	22.85	12.90	6.21
Deviator Stress Lower Limit (psi)	2.00	2.00	2.00	2.00
E-Failure (ksi)	7.605	4.716	1.827	1.00
ϕ (Degrees)	0.0	0.0	0.0	0.0
c (psi)	16.4	11.425	6.45	3.105

model. This loading is equivalent to a 9 kip (9,000 pounds) concentrated load representing one dual-wheel of the standard 18 kip (18,000 pound) single axle load. Figure 3.1 shows a typical mesh for a typical pavement system.

3.2 MATERIAL MODELS

3.2.1 Asphaltic Concrete Layer

Even though the elastic properties of the AC layer are known to vary with temperature, they are assumed to be constant throughout the entire layer during any one analysis. The effect of temperature is investigated by using different Young's modulus and Poisson's ratio values while keeping all other problem parameters constants. For thin AC layers, assuming constant elastic parameters may be appropriate. However, for thick layers, the temperature variation can be appreciable, and this assumption may not be acceptable. A summary of Young's modulus and Poisson's ratio values used in the analyses is presented in Table 3.1.

3.2.2 Gravel Base Layer

Experimental results obtained by numerous researchers (Hicks, 1970; Smith, 1977) support the argument that the behavior of unbound granular material is stress-hardening. It was concluded that the resilient modulus of the highly non-homogeneous gravel/crushed stone layer depends primarily on the degree of confinement. A convenient measure of confinement is the first invariant of the stress tensor, J_1 , which is the sum of the three principal stresses. The resilient modulus can be expressed as:

$$E_{bsc} = K J_1^n \quad (3.1)$$

where K and n are experimentally determined material parameters.

It can be noted, from this relationship, that the resilient modulus of common base materials increases with increasing confining pressure, which is reflected by

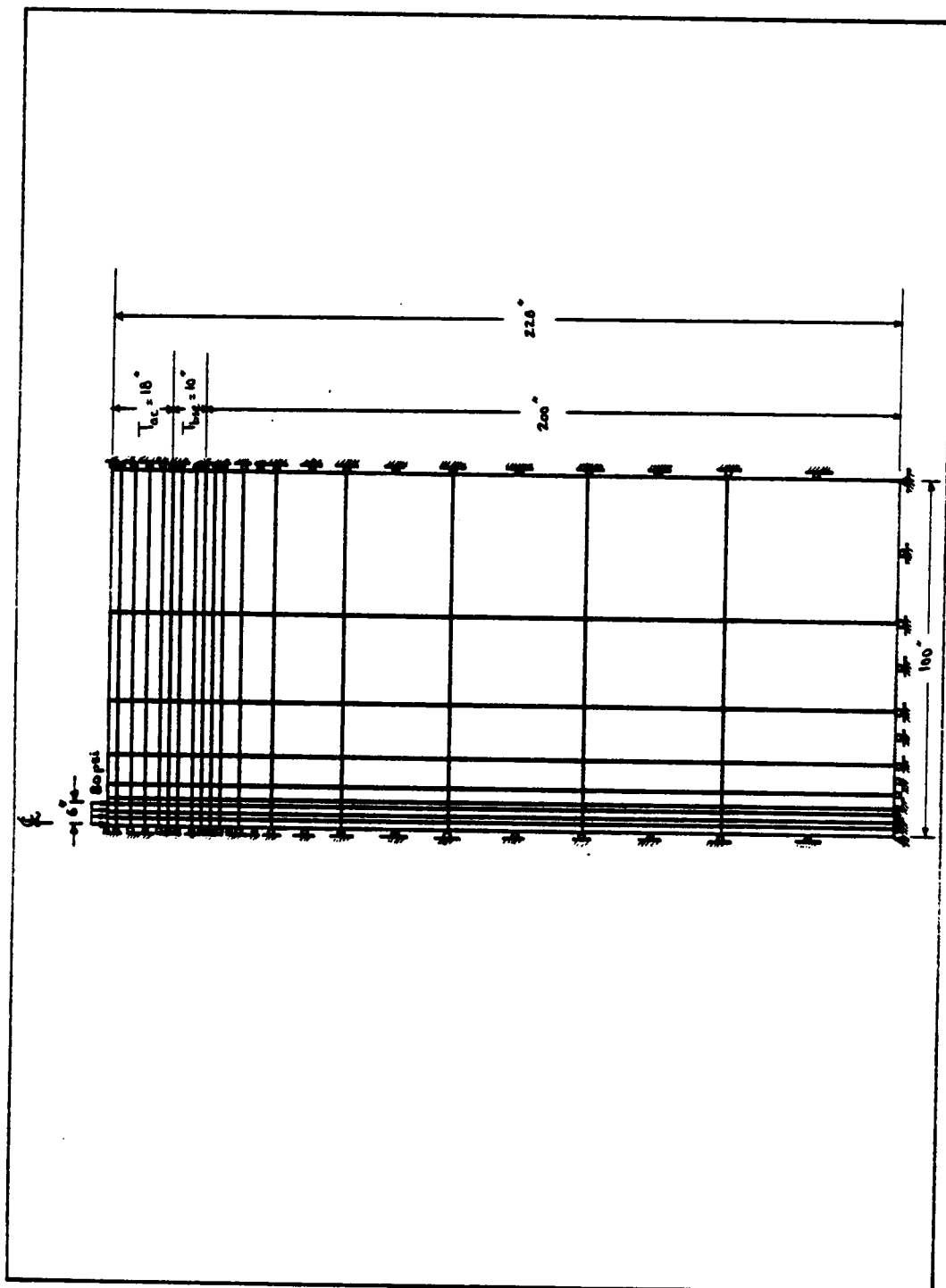


Figure 3.1. Modeling of the Flexible Pavement Problem

J_1 . Figure 3.2 shows the E_{bse} vs J_1 curve for $K = 4000.0$ and $n = 0.50$. These values of K and n which are consistent with results of laboratory data from tests on typical Tennessee base materials have been used in all analyses.

3.2.3 Subgrade Material

Laboratory testing (Thompson and Robnett, 1976) has shown that, unlike gravel and crushed stone base materials, fine-grained subgrade materials exhibit a stress-softening behavior. In addition, this behavior has been found to depend primarily on the deviator stress, S_d , which is the difference between the major and minor principal stresses. As an idealization of the non-linear resilient modulus-deviator stress curve, two straight line segments are often fitted to the experimental data, and the relationship between the subgrade resilient modulus E_r and S_d can be written as:

$$E_r = E_{ri} + K_1 \left(S_d - S_{di} \right) \text{ for } S_d < S_{di} \quad (3.2)$$

$$E_r = E_{ri} + K_2 \left(S_d - S_{di} \right) \text{ for } S_d > S_{di}$$

where E_{ri} is the breakpoint modulus or the resilient modulus corresponding to the breakpoint deviator stress, S_{di} , which is assumed to be constant at 6.2 psi for all subgrade types. The slopes of the two line segments, K_1 and K_2 , are also constant for different subgrade materials; the only varying quantities are the breakpoint modulus and the maximum allowable deviator stress. Figure 3.3 shows the bilinear models proposed by Thompson (Thompson and Robnett, 1976) and adopted for these analyses.

MATERIAL MODEL FOR GRAVEL BASE

$$E_{bse} = K \times J_1^n \quad (K = 4000.0, n = 0.50)$$

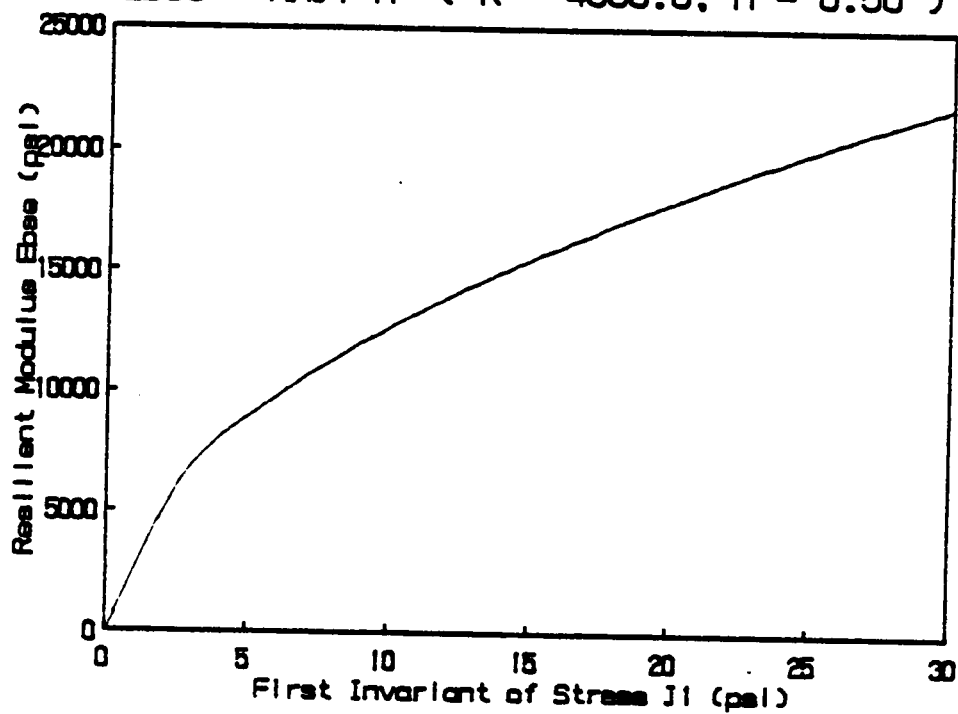


Figure 3.2. Material Model for Gravel Base

BILINEAR MODELS FOR SUBGRADE MATERIAL

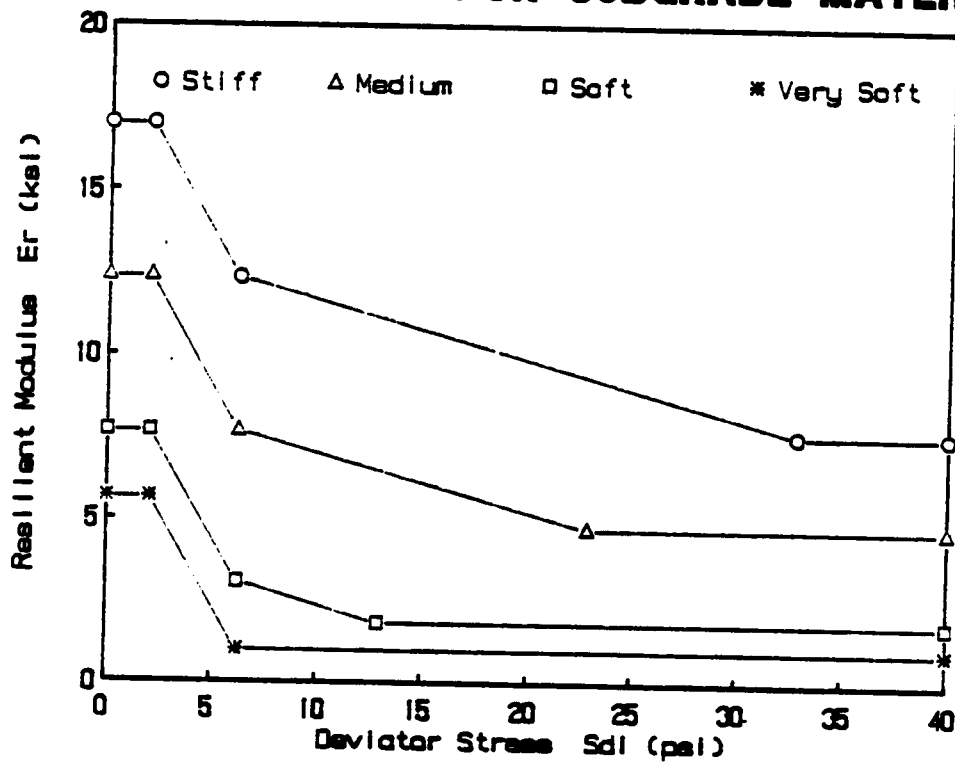


Figure 3.3. Bilinear Models for Subgrade Material

3.3 SOLUTION SCHEME

3.3.1 Description

The procedure used in solving the non-linear pavement system is significantly different from that used in the residual soil-bedrock cavity problem. While the behavior of the materials present in the cavity problem can be described by a constitutive model where plastic strains are governed by a well defined flow rule, the behavior of each of the non-linear materials present in the flexible pavement problem is described by a single equation relating some stress measure to the current stiffness. Since the stress measures used in the pavement problem, such as the deviator stress and the first invariant of the stress tensor, do not define a unique state of stress, some difficulties arise in selecting an appropriate solution procedure. An ideal solution scheme is an algorithm that is guaranteed to converge and that converges to a unique solution. In the case of the non-linear pavement problem, this ideal solution algorithm is simply non-existent unless the material models are modified to contain more information.

The solution procedure used in this application is that of a trial-and-error one, or more technically termed as a direct iterative procedure. In this procedure, each successive approximation is obtained by using the previous approximation of the solution. Initially, modulus values for the different materials are assumed; then the solution of a linear elastic problem is performed and approximate stresses are obtained. These stresses, after some modifications to account for the limited tensile strength of the base course, are used in the model equations to obtain new values for the material moduli E_r . This iterative process continues until convergence is achieved. Figure 3.4 shows a flowchart of the process. Theoretically, this method provides no guarantee of convergence (Owen and Hinton, 1980), and the material models used indicate that there is no guarantee of uniqueness. Clearly, the most critical value in the validity of an

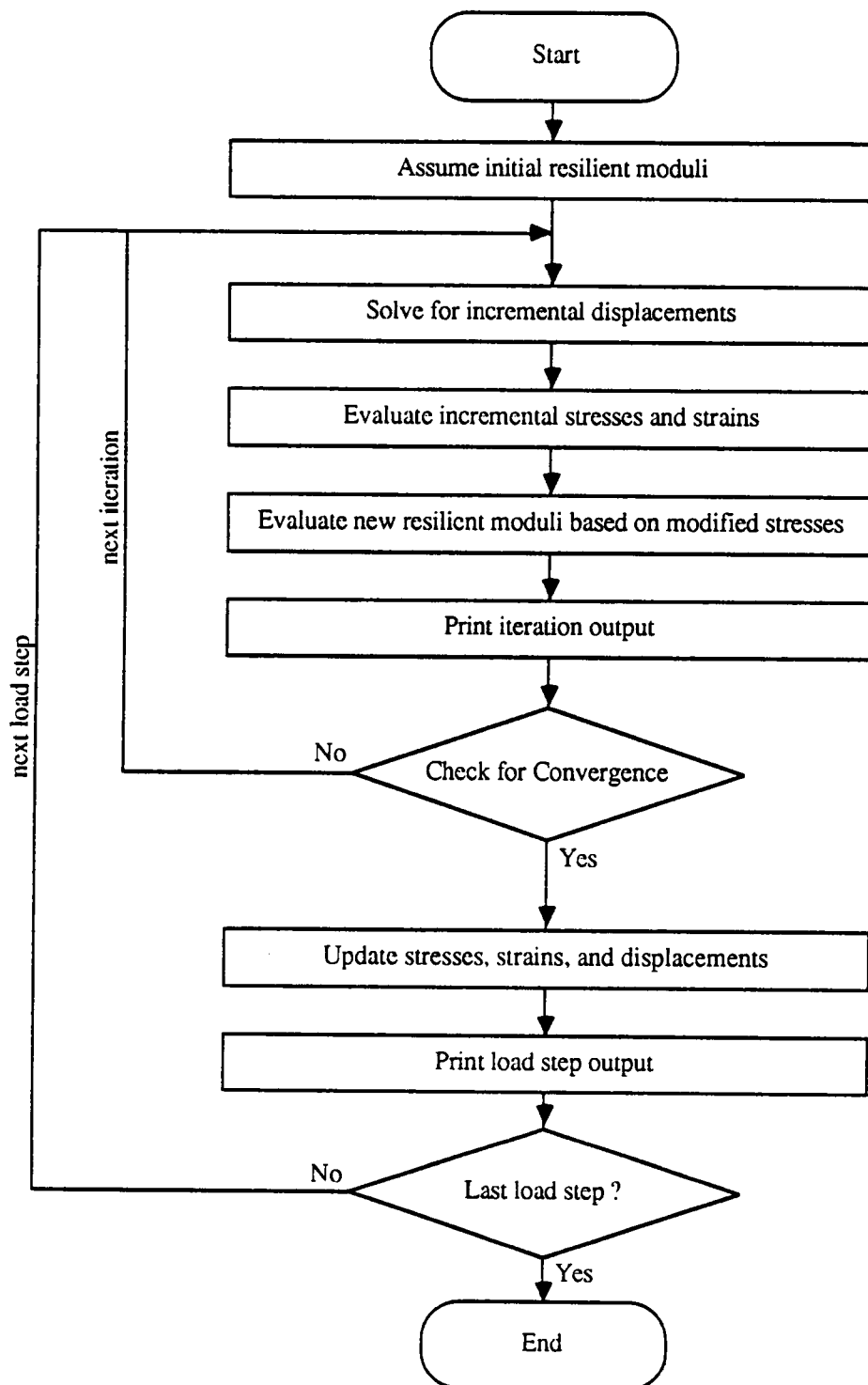


Figure 3.4. Flowchart of the Solution Scheme for the Flexible Pavement System

obtained solution is the initial guess at which the approximation process is started. The closer this initial guess of the modulus is to an average measure of the variation of the modulus across a material layer, the faster the convergence is and the higher the confidence in uniqueness. A good starting value of the modulus can be obtained by approximating the insitu stresses using classical semi-infinite half space methods.

3.3.2 Convergence Criteria

Since the iterative process predicts new resilient moduli at each integration point, convergence is indicated by a decreasing variation, in a general sense, of resilient moduli from one iteration to the next. Instead of monitoring convergence at each integration point individually, a norm is calculated by summing up contributions from all integration points and monitoring the change in this norm. The chosen criterion can be expressed as follows:

$$\frac{\left| \sqrt{\sum_{i=1}^n (E_i^r)^2} - \sqrt{\sum_{i=1}^n (E_i^{r-1})^2} \right|}{\sqrt{\sum_{i=1}^n (E_i^0)^2}} \leq 0.01 \quad (3.3)$$

where $\sqrt{\sum_{i=1}^n (E_i^0)^2}$ is the norm of resilient moduli at the start of the iterative process, and $\sqrt{\sum_{i=1}^n (E_i^r)^2}$ is the norm of resilient moduli at iteration r , and n is the number of integration points.

In addition to this criterion, the code uses a displacement-based convergence check. This check is also global, i.e., norms are compared instead of nodal values. This criterion may be written as:

$$\frac{\left| \sqrt{\sum_{i=1}^n (D_i^r)^2} - \sqrt{\sum_{i=1}^n (D_i^{r-1})^2} \right|}{\sqrt{\sum_{i=1}^n (D_i^0)^2}} \leq 0.01 \quad (3.4)$$

where $\sqrt{\sum_{i=1}^n (D_i^0)^2}$ is the norm of displacements at the first iteration, $\sqrt{\sum_{i=1}^n (E_i^r)^2}$ is the norm of displacements at iteration r , and n is the number of nodes. The iteration process is completed when both criteria are satisfied.

3.3.3 Mohr-Coulomb Stress Modification Procedure

The solution of the pavement problem almost invariably indicates the existence of excessively high tensile stresses in the gravel/crushed stone base layer. However, intuition indicates that these materials have very little or no tensile strength. The very limited tensile strength that may exist is brought about by granular interlocking which occurs when the stresses in the direction perpendicular to that of the tensile stresses are relatively high. In order to prevent the prediction of these tensile stresses, an algorithm (Raad and Figueroa, 1980) has been incorporated into the code. The Mohr-Coulomb failure criterion is assumed for both the subgrade and base materials. In terms of principal stresses, this curve is expressed by the following equation:

$$\sigma_1 = \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) + 2c \tan \left(45 + \frac{\phi}{2} \right) \quad (3.5)$$

where σ_1 and σ_3 are the major and minor stresses, respectively; and c and ϕ are the cohesion and friction angle, respectively. Figure 3.5 is a plot of the Mohr-Coulomb failure criterion in the p - q stress space where

$$p = \frac{\sigma_1 + \sigma_3}{2} \quad (3.6)$$

$$q = \frac{\sigma_1 - \sigma_3}{2} \quad (3.7)$$

It is assumed that the vertical stress, σ_v , is the most accurately predicted stress component. The vertical stress σ_v , the major principal stress σ_1 , the minor principal stress σ_3 , the cohesion c , and the angle of internal friction ϕ are used as input to the procedure. Based on the vertical stress and the material parameters,

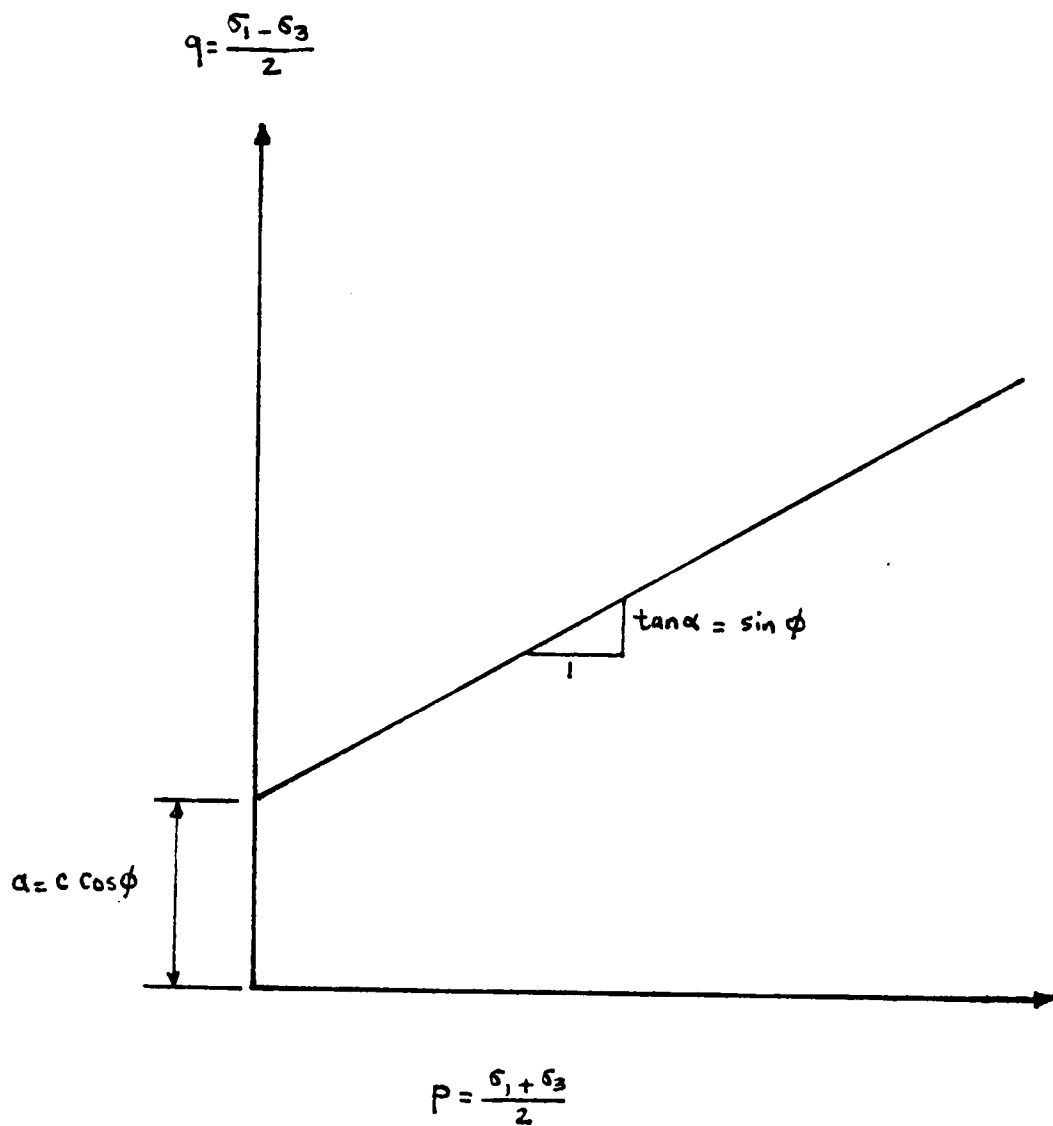


Figure 3.5. Mohr-Coulomb Curve in p - q Stress Space

the maximum and minimum stresses permissible under the Mohr-Coulomb curve are calculated as follows:

$$(\sigma_1)_{max} = \sigma_v \tan^2\left(45 + \frac{\phi}{2}\right) + 2c \tan\left(45 + \frac{\phi}{2}\right) \quad (3.8)$$

and

$$(\sigma_3)_{min} = \sigma_v \tan^2\left(45 - \frac{\phi}{2}\right) - 2c \tan\left(45 - \frac{\phi}{2}\right) \quad (3.9)$$

The following three conditions have to be met for the stress state not to be modified by the Mohr-Coulomb stress modification procedure:

$$\begin{aligned} \sigma_1 &\leq (\sigma_1)_{max} \\ \sigma_3 &\geq (\sigma_3)_{min} \\ \sigma_1 &\leq \sigma_1 \end{aligned} \quad (3.10)$$

where σ_1 is the value of σ_1 associated with σ_3 at failure;

and can be expressed as:

$$\sigma_1 = \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right) + 2c \tan\left(45 + \frac{\phi}{2}\right) \quad (3.11)$$

A flowchart of the modification procedure is shown in Figure 3.6. Note that in order to account for materials which are known to have some tensile strength, a very simple change in the procedure is required. Instead of setting $(\sigma_3)_{min}$ to zero (Figure 3.6), a tension cut-off value can be used. A separate Fortran program has been written and tested prior to the actual implementation of the procedure in the finite element code. Input to the program consists of the coordinate stresses and the material friction angle and cohesion. The program calculates the principal stresses, modifies them according to the Mohr-Coulomb procedure, and calculates the resulting equivalent coordinate stresses. Appendix A contains a listing of this program and some verification examples.

It should be noted that the Mohr-Coulomb stress modification procedure, as implied by its name, modifies the stress field only. As shown in the flowchart of the solution scheme, Figure 3.4, the stresses resulting from the finite element

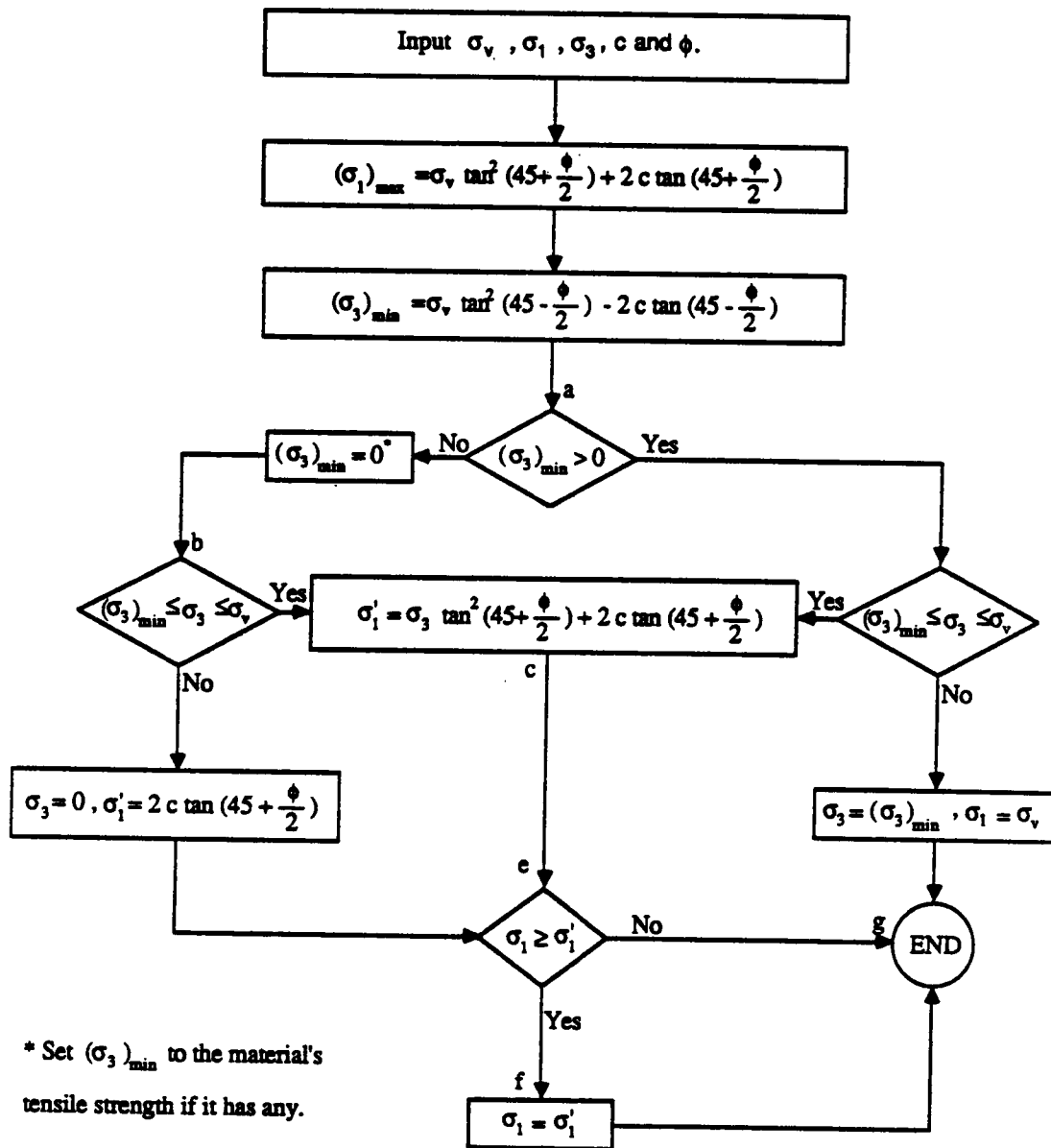


Figure 3.6. Flowchart of the Mohr-Coulomb Stress Modification Procedure

solution are modified and the moduli values based on the modified stresses are evaluated. The strains obtained at the end of a given iteration have never been considered in the modification procedure; rather, they are based on the displacements that have been solved for using the moduli values from the previous iteration.

There are acceptable justifications for not modifying the strain field to correspond to the modified stress field. The first justification is that the material models are functions of the stresses only; therefore, the final solution does not depend on whether the strains are modified or not. The second justification is that the two strain quantities that are of major interest in the flexible pavement analyses, namely, the AC radial strain and the vertical strain in the subgrade, are unaffected by the procedure. The AC radial strain is unaffected because the linear elastic AC layer is assumed to have unlimited strength. The vertical strain in the subgrade is unaffected because the vertical stress is not modified by the procedure since it is assumed to be the most accurately predicted stress component.

It should be noted, however, that even though the strains are not modified, the use of the procedure results in different moduli values for the base course and the subgrade and consequently in a different system response. In Figure 3.7, the effect of using the Mohr-Coulomb modification procedure is illustrated by plotting radial stress versus depth for a typical pavement problem. It can be noted that even though the Mohr-Coulomb stress modification is not applied in the AC layer, the AC radial stress is reduced when the modification is employed in the base course and the subgrade. The use of the procedure has resulted in the elimination of the base course tensile stresses; therefore, the resulting confining pressure is greater and the base modulus values are also greater. This explains why the use of the procedure results in lower radial stresses in the AC layer.

Effect of Mohr-Coulomb Modification

on radial Stress

$T_{ac}=3\text{ in.}$, $T_{bs}=10\text{ in.}$, $E_{ac}=100\text{ ksi}$, $E_r=1.0\text{ ksi}$

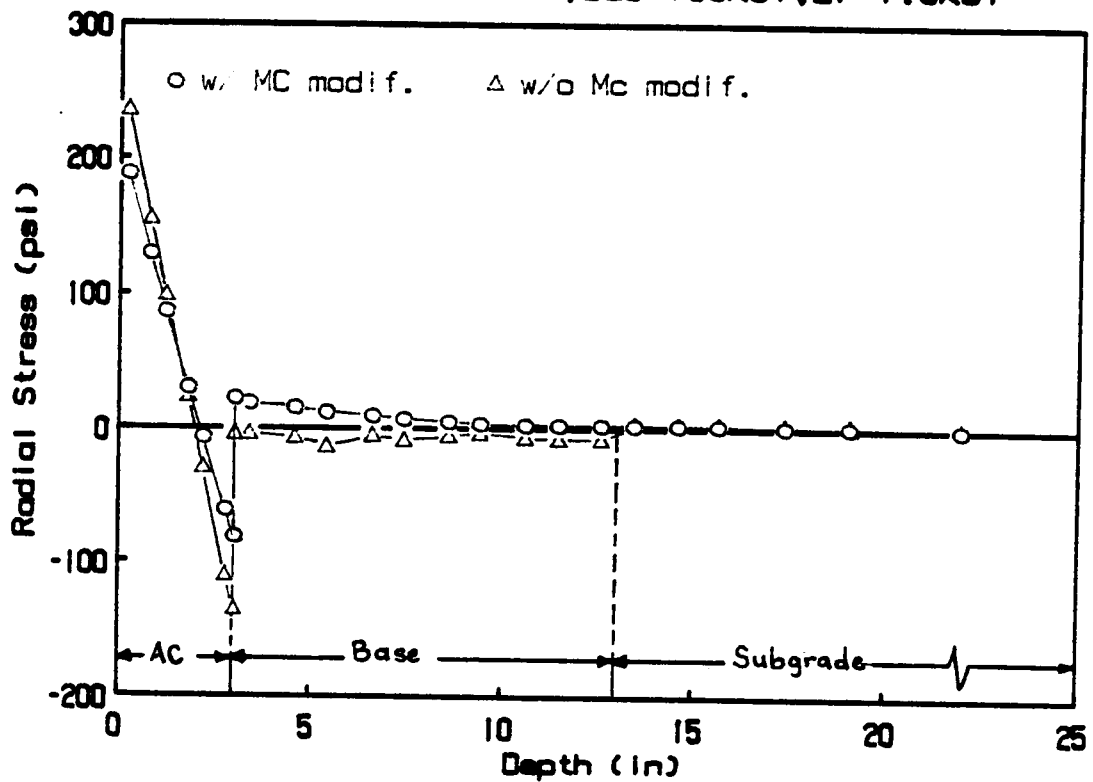


Figure 3.7. Effect of Mohr-Coulomb procedure on Radial Stress

Finally, it is worthy to note that the use of the Mohr-Coulomb stress modification has resulted in (an improved) rate of convergence. Hence, considerable savings in computer time have been realized. For instance, the solution of the comparison problem without the procedure required nine iterations (4 hours and 40 minutes total run time) while that of the same problem with the procedure required only six iterations (3 hours and 39 minutes total run time). The more realistic moduli values resulting from the modified stresses may explain the faster convergence of the problem.

3.4 RESULTS AND DISCUSSIONS

The major incentive for obtaining the structural response of the flexible pavement system for many combinations of variable values is the development of simple analysis algorithms that can reliably predict the structural response without recourse to the finite element code. Once these algorithms are developed, considerable cost savings and solution ease can be realized. Even though mechanistic analysis and design algorithms constitute the final goal of the finite element analyses, the scope of this investigation is limited to the study of the non-linear stress-deformational response of flexible pavement systems. The actual development and testing of the algorithms is performed elsewhere (Drumm and Moore, 1987).

Before presenting the effects of the varied factors on the stress-deformational response of the flexible pavement system, a discussion of the manner in which the wheel load is applied to the pavement system is provided. The application of the surface load through a rigid plate results in a uniform surface displacement under the plate and may best simulate deflection data obtained by the falling weight deflectometer (FWD) testing device. However, the use of a rigid plate may not be an appropriate representation of an actual

wheel load since a tire is flexible relative to the pavement. The effect of a rigid plate has been investigated for a homogeneous half-space by comparing the variation of FEM radial strain with depth for conditions with and without plate. The radial strain is also compared to that obtained in closed form (Yoder and Witczak, 1975). From Figure 3.8, it can be noted that, as expected, the FEM radial strains corresponding to the case of a uniformly applied load compare very well with those obtained in closed form. It can be noted from this same figure that when the load is applied through a rigid plate, significantly smaller radial strains result. The effect of a rigid plate has also been investigated for a layered pavement system. The effects of the plate on the surface, base, and subgrade deflections and on the radial strain are shown in Figures 3.9, 3.10, 3.11, and 3.12 respectively. It can be noticed that the effect of the plate is more pronounced toward the surface and closer to the centerline of the model. More importantly, it should be noted that the use of a rigid plate always results in smaller deflections and smaller strains. The subgrade deflection and the AC radial strain are considered to be the two most important indicators of flexible pavement performance. Hence, the accurate prediction of these two quantities is of great importance; and since a uniform load simulates the service conditions better than the application of the wheel load through a rigid plate does, the former assumption has been adopted in the analyses whose results are now presented.

The parameters that have been varied are the asphaltic concrete modulus E_{ac} , its thickness T_{ac} , the thickness of the base course T_{bse} , and the subgrade breakpoint modulus E_{ri} . A total of 204 PCPAVAN analyses have been performed including 12 without the AC layer. The results of all the analyses, except for the no AC problems, are presented in tabular form in Appendix B. The quantities recorded include the centerline deflection at the surface, D_0 , the

Comparison of Closed Form Solution to FE Solution

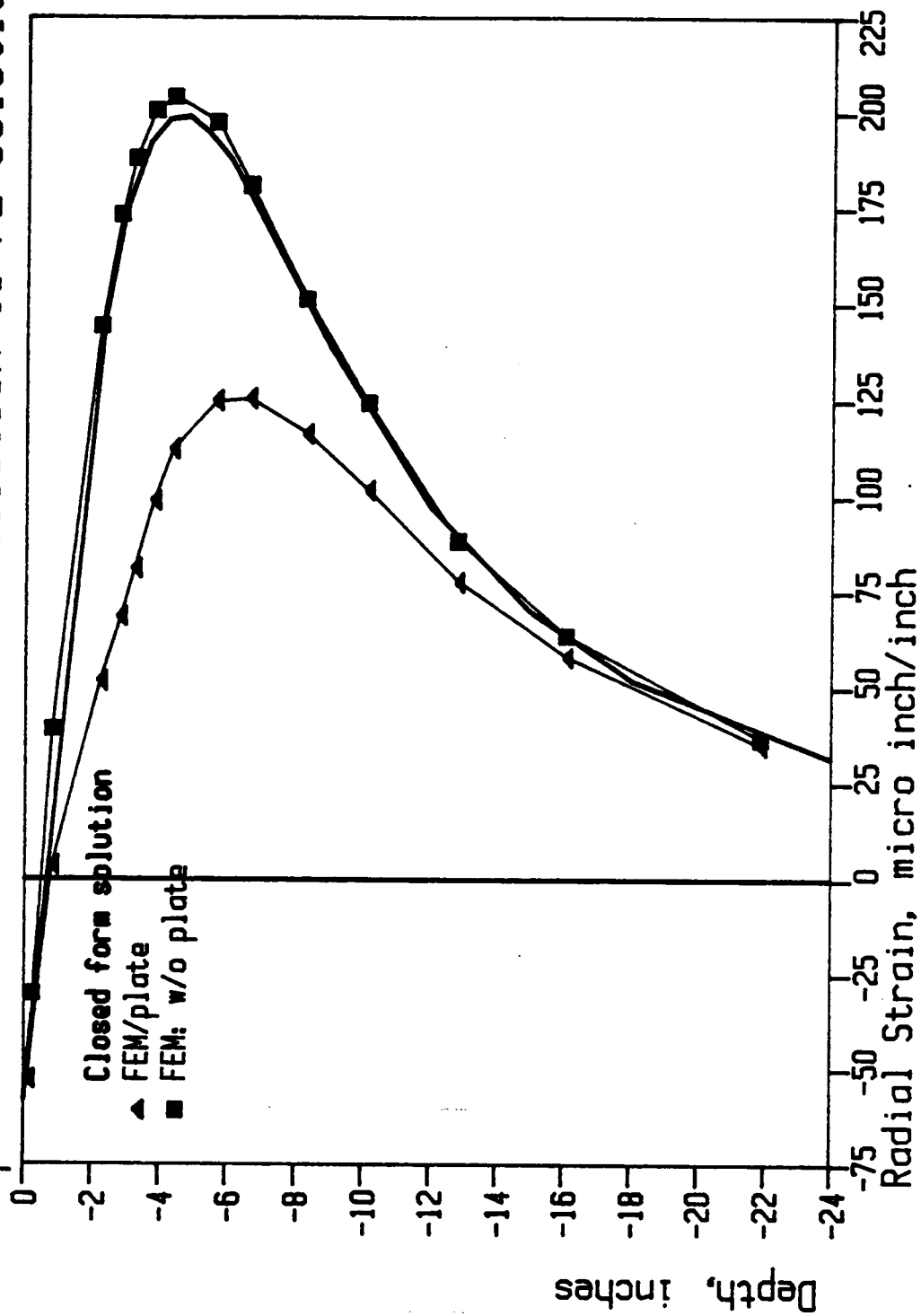


Figure 3.8. Effect of Rigid Plate on Radial Strain for a Homogeneous Half-Space

Effect of Plate on Surface Deflection

$T_{oc}=8\text{ in.}$, $T_{bs}=4\text{ in.}$, $E_{oc}=1000\text{ ksi}$, $E_r=7.88\text{ ksi}$

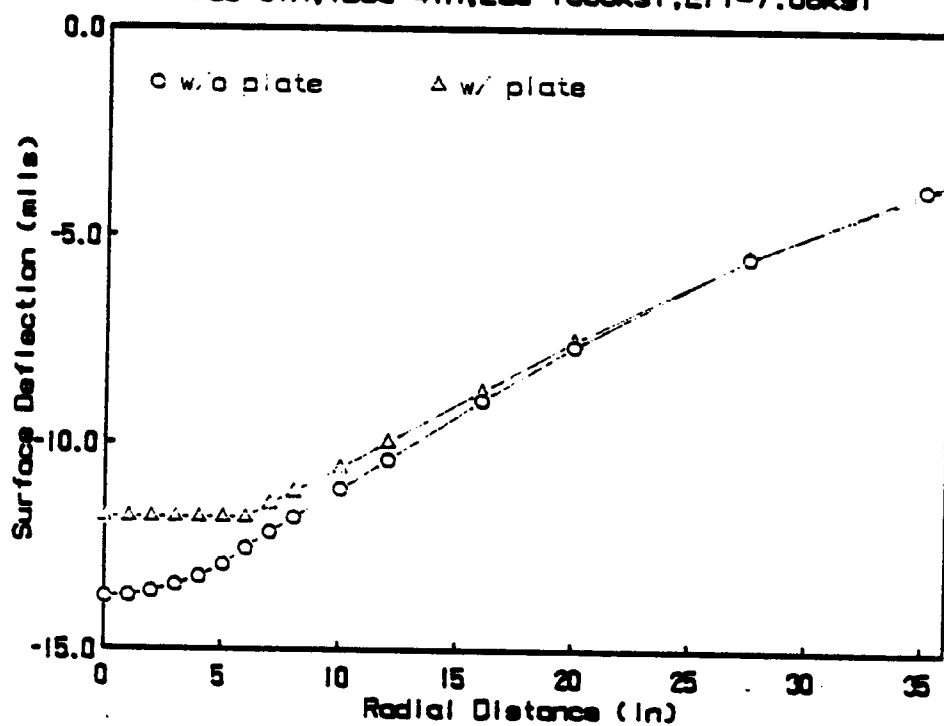


Figure 3.9. Effect of Rigid Plate on Surface Deflection

Effect of Plate on Base Deflection

$T_{oc}=6\text{ in.}$, $T_{oe}=4\text{ in.}$, $E_{oc}=1000\text{ ksi}$, $E_{ri}=7.68\text{ ksi}$

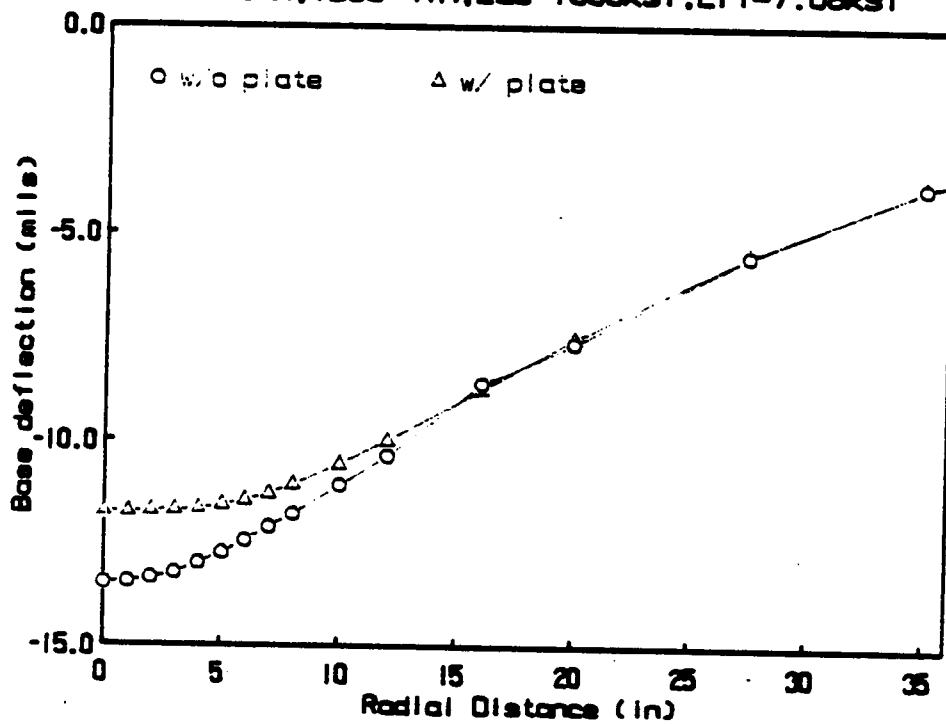


Figure 3.10. Effect of Rigid Plate on Base Deflection

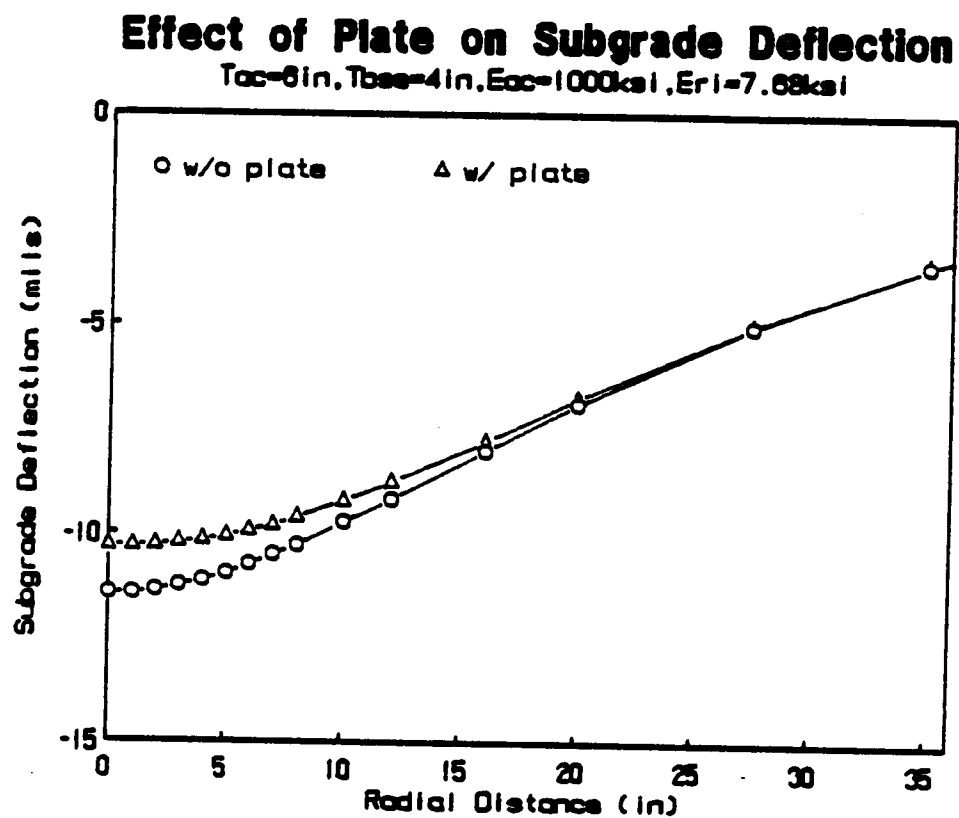


Figure 3.11. Effect of Rigid Plate on Subgrade deflection

Effect of Plate on Radial Strain

$T_{ac}=6\text{ in.}$, $T_{base}=4\text{ in.}$, $E_{ac}=1000\text{ ksi}$, $E_{ri}=7.68\text{ ksi}$

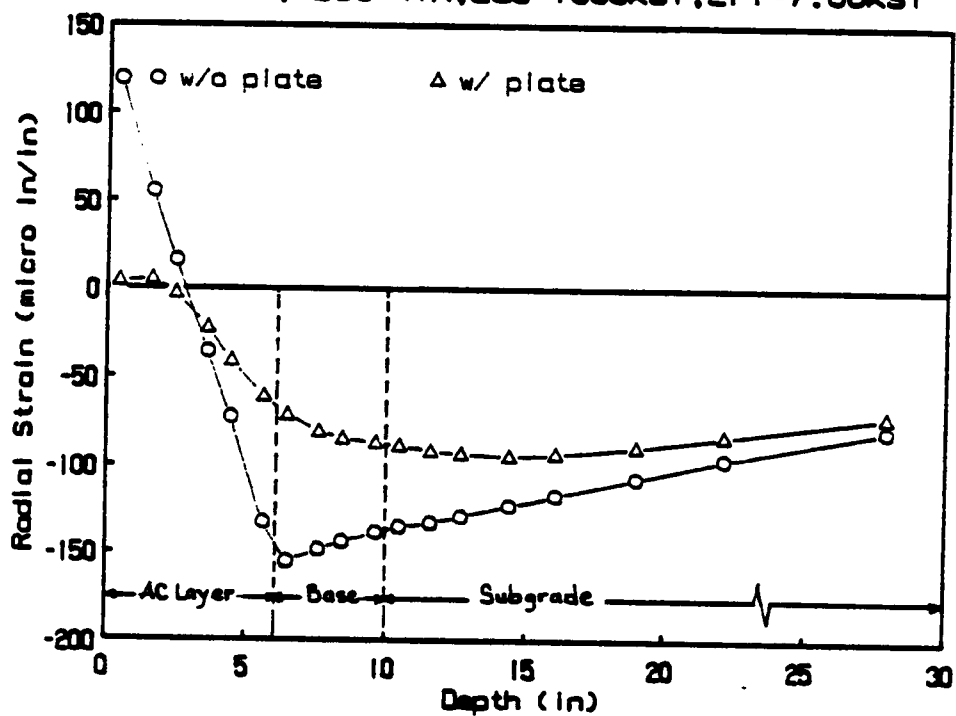


Figure 3.12. Effect of Rigid Plate on Radial Strain

centerline deflection at the subgrade level, D_s , the maximum radial tensile strain at the bottom of the AC layer, ϵ_{ac} , the maximum vertical strain at the top of the subgrade, ϵ_z , the subgrade deviator stress, S_d , and the maximum vertical stress at the top of the subgrade, s_z .

From these results, several plots showing the effects of a variation of the input parameters have been obtained. The procedure followed in investigating these effects is to vary the input variable and study the variation in the output variable while keeping all other input variables constant. The resulting conclusions are presented in the following sections.

3.4.1 Effect of AC Thickness on Surface Deflection

Figure 3.13 shows four arithmetic plots of the surface deflection, D_0 , versus the thickness of the AC layer, T_{ac} , corresponding to the four E_{ac} values. These plots are for a soft subgrade and a 4 inch thick base course. From these curves, a strong correlation between D_0 and T_{ac} is clear; as T_{ac} increases, D_0 decreases. Furthermore, it is noted that for this particular combination of subgrade and base course, D_0 is smaller for greater E_{ac} and that the effect of the AC modulus is greater for thinner AC layers. When plotted on a logarithmic scale, Figure 3.14, linear relationships similar to those reported by Elliot and Thompson (1984) are revealed. In order to study the effect of the subgrade type, D_0 has been plotted versus T_{ac} for $E_{ac}=100$ ksi, and $T_{bse}=4$ inches in Figure 3.15. The set of four curves representing the four subgrade types indicates that D_0 is greater for softer subgrades and that the effect of the subgrade becomes smaller as T_{ac} increases. Again, logarithmic plots, Figure 3.16, have revealed linear relationships between $\log(D_0)$ and $\log(T_{ac})$ for the different subgrades.

Surface Deflection vs AC Thickness

for Soft Subgrade and $T_{base} = 4$ in.

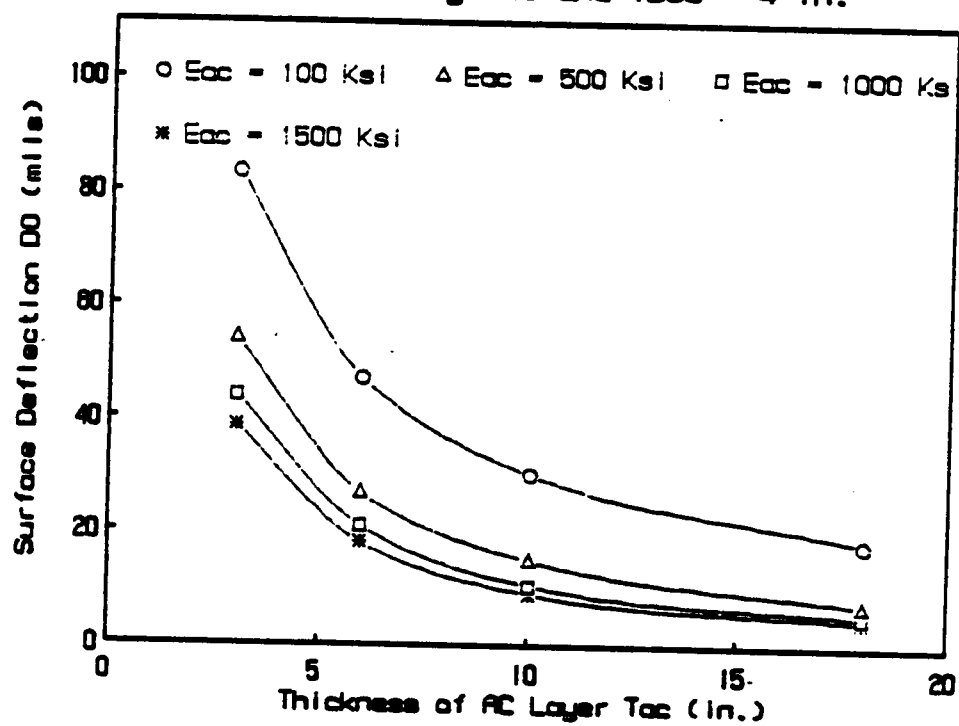


Figure 3.13. Arithmetic Plot of Surface Deflection versus AC Thickness for Constant Subgrade

Surface Deflection vs AC Thickness

for Soft Subgrade and $T_{base} = 4$ in.

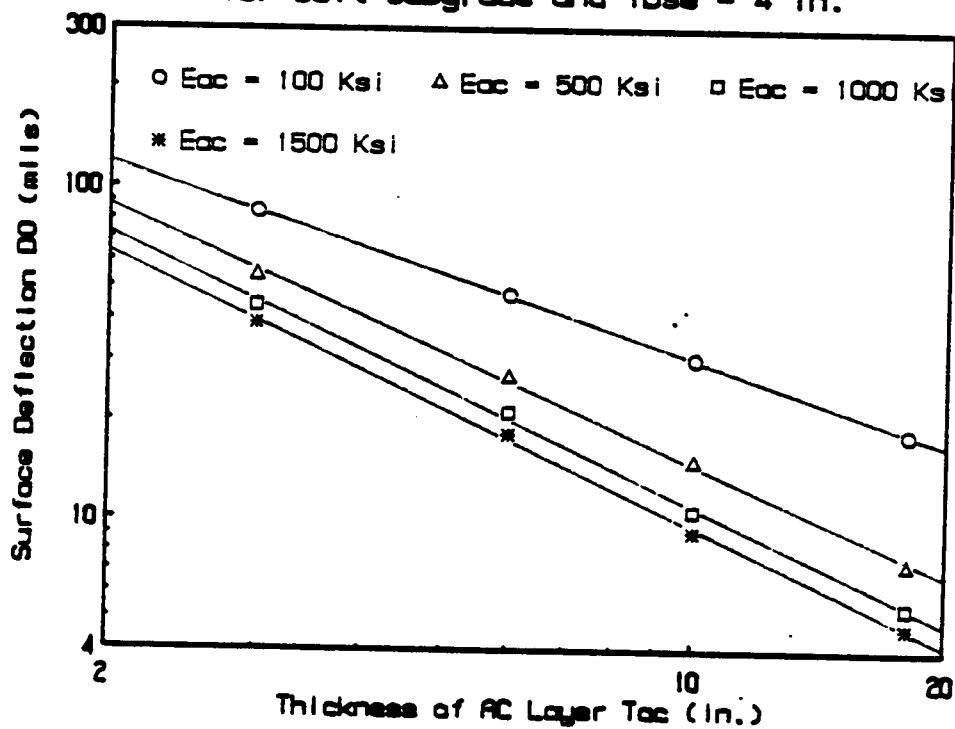


Figure 3.14. Logarithmic Plot of Surface Deflection versus AC Thickness for Constant Subgrade

Surface Deflection vs AC Thickness

for $E_{ac} = 100$ Ksi and $T_{base} = 4$ in.

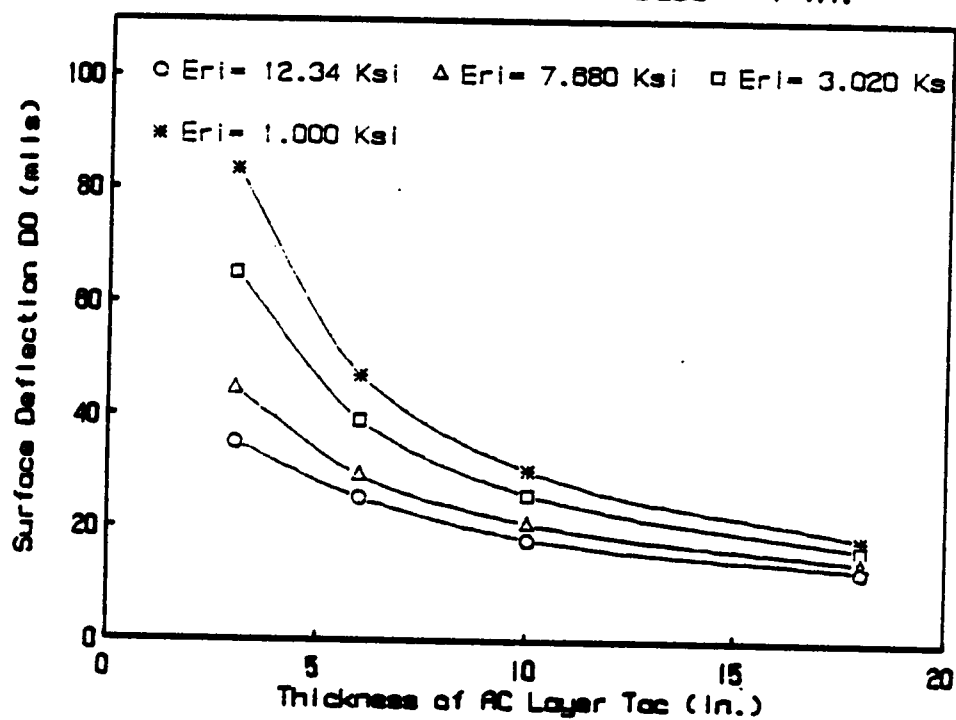


Figure 3.15. Arithmetic Plot of Surface Deflection versus AC Thickness for Constant AC Modulus

Surface Deflection vs AC Thickness

for $E_{ac} = 100$ Ksi and $T_{base} = 4$ in.

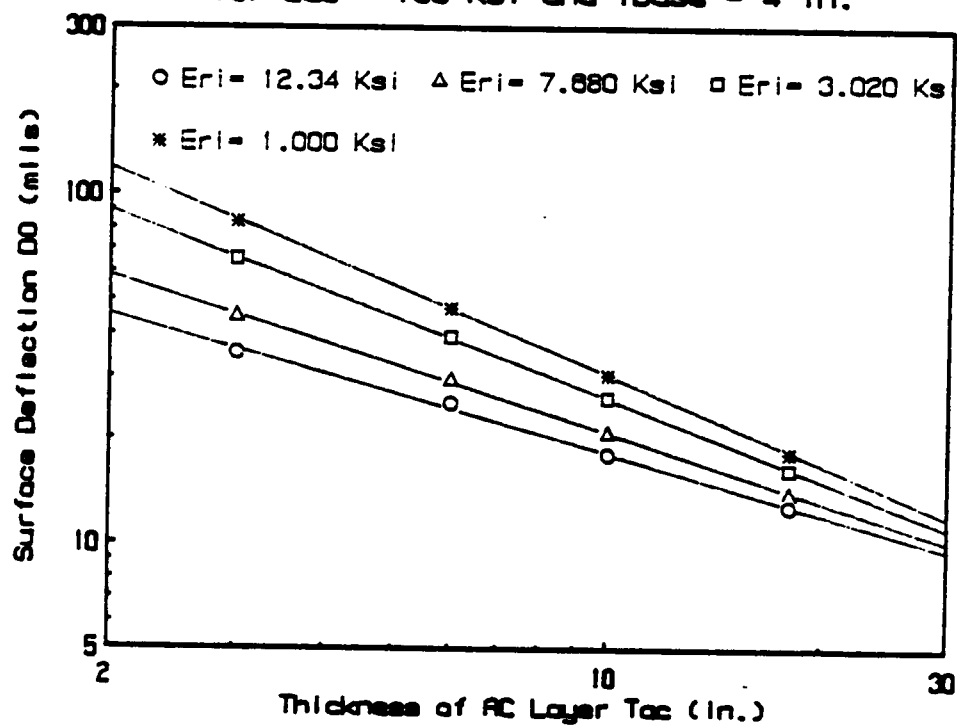


Figure 3.16. Logarithmic Plot of Surface Deflection versus AC Thickness for Constant AC Modulus

3.4.2 Effect of AC Thickness on Subgrade Deflection

Subgrade deflection is of major interest since it has been identified as an important predictor in rutting of flexible pavements. Similar logarithmic plots for the subgrade deflection D_s are shown in Figures 3.17 and 3.18. The thickness of the AC layer has similar effects on the subgrade deflection as it has on the surface deflection. The only noticeable difference, as indicated by the approximately parallel curves, is that for thick AC layers, E_{ac} and E_{ri} have little effect on the subgrade deflection.

3.4.3 Effect of AC Thickness on the AC Radial Strain

Curves for the maximum radial strain in the AC layer have been plotted versus AC thickness and shown in Figures 3.19 and 3.20. It can be noted that the logarithmic relationships are not as linear as those obtained for the surface and subgrade deflections. However, it can be concluded that a thicker or stiffer AC layer always translates into smaller radial strain.

3.4.4 Effect of Base Thickness on Pavement Response

The effect of the thickness of the base course is not consistent for all the analyses. A thicker base course doesn't necessarily mean smaller deflections or AC radial strain. The effect depends on the stiffness of the base course relative to that of the subgrade. Opposite to what is intuitively expected, a thicker base course may result in larger AC radial strain. This result may be attributed to the stress-hardening model used for the base course which does not have a cut-off value for the resilient modulus at low stress levels. The assignment of a minimum value of base course modulus may affect the finite element results. However, the value of this cut-off modulus may be difficult to evaluate experimentally. Hence, no cut-off value has been adopted.

Subgrade Deflection vs AC Thickness

for Soft Subgrade and $T_{base} = 4$ in.

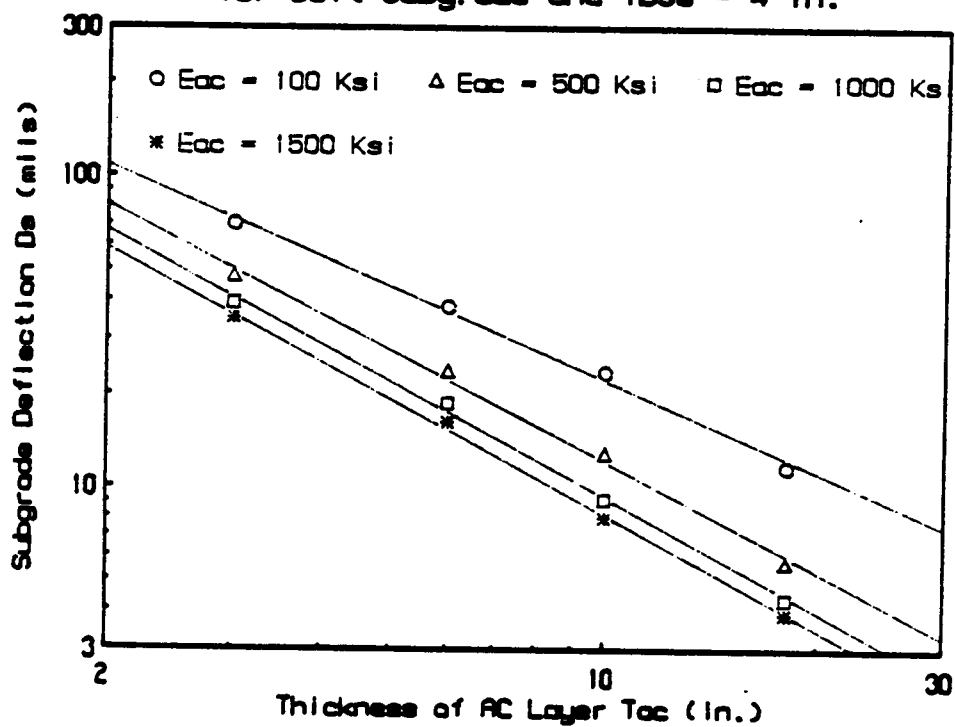


Figure 3.17. Logarithmic Plot of Subgrade Deflection versus AC Thickness for Constant Subgrade

Subgrade Deflection vs AC Thickness

for $E_{ac} = 100$ Ksi and $T_{base} = 4$ in.

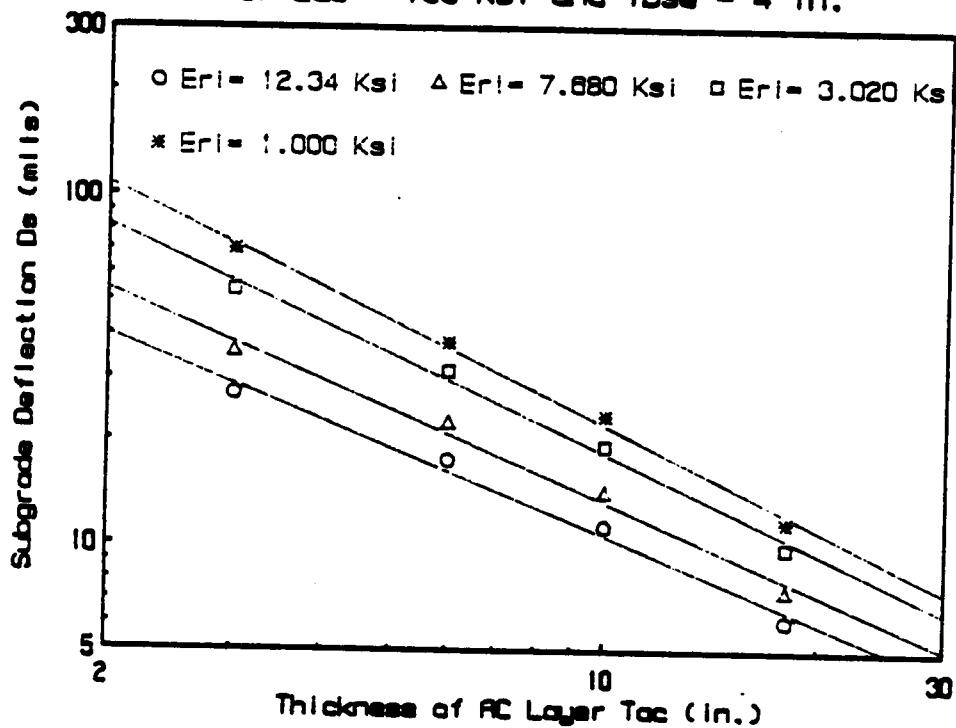


Figure 3.18. Logarithmic Plot of Subgrade Deflection versus AC Thickness for Constant AC Modulus

AC Radial Strain vs AC Thickness

for Soft Subgrade and $T_{base} = 4$ in.

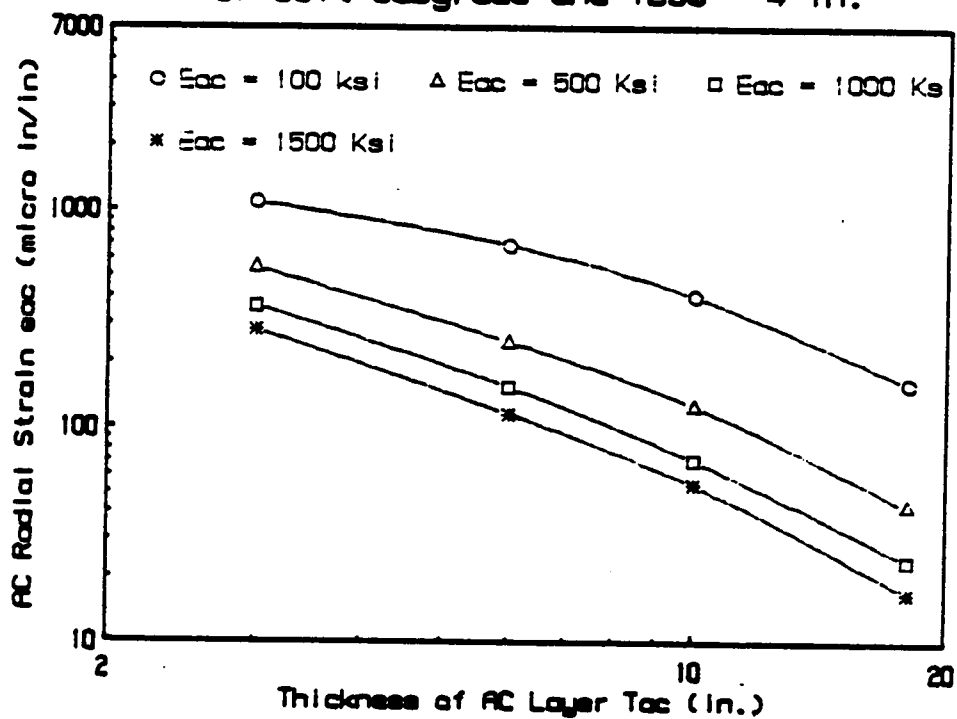


Figure 3.19. Logarithmic Plot of AC Radial Strain versus AC Thickness for Constant Subgrade

AC Radial Strain vs AC Thickness

for $E_{ac} = 100$ Ksi and $T_{base} = 4$ in.

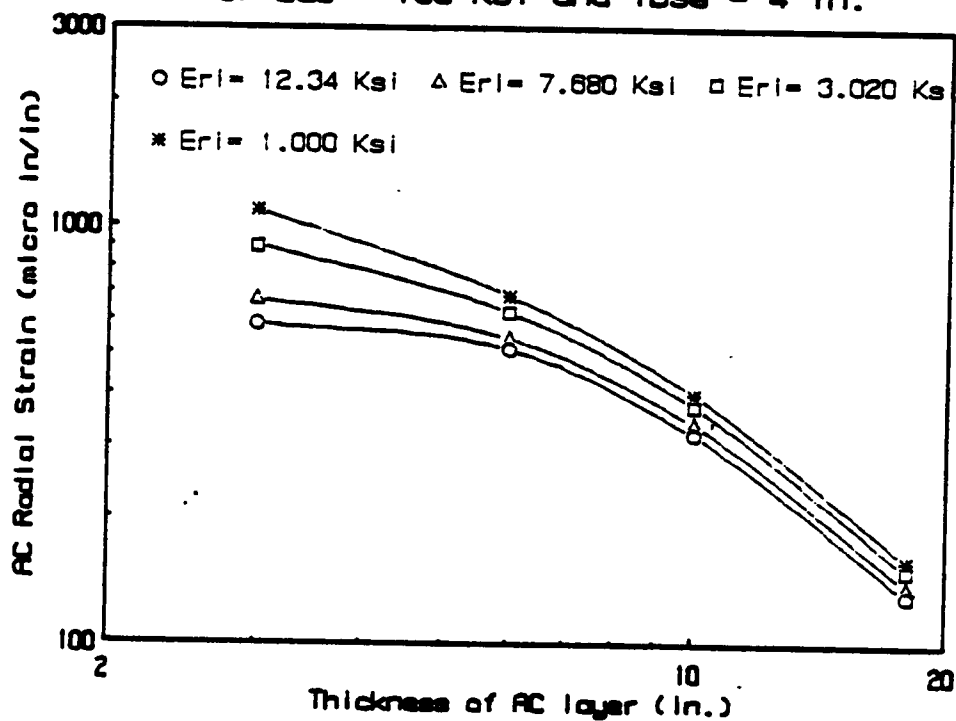


Figure 3.20. Logarithmic Plot of AC Radial Strain versus AC Thickness for Constant AC Modulus

3.5 PROGRAM ENHANCEMENTS

The major modifications to the original mainframe version of the code, SSTIN, that were necessary in order to make it suitable for the flexible pavement problem are discussed in this section. The resulting micro-computer version, PCPAVAN, is intended to run on an IBM PC XT or compatible with a minimum of 640 K of memory for a mesh having approximately 600 nodes.

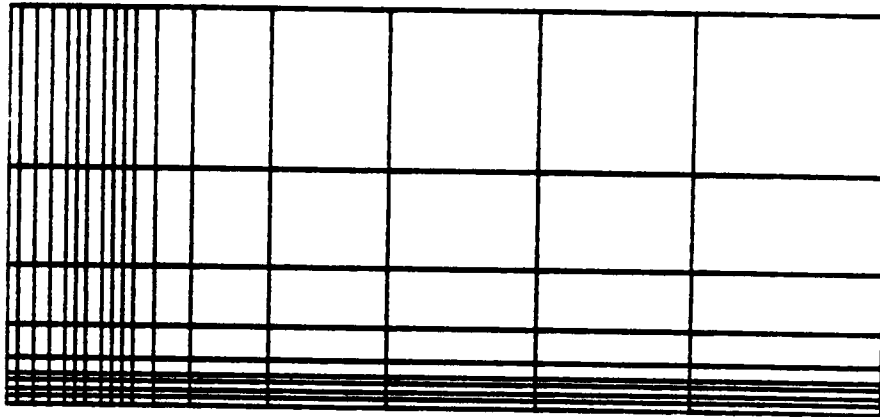
Unlike a mainframe computer, a micro-computer has a limited amount of memory. As a result, the problem size can be severely limited unless proper programming techniques that minimize core memory requirements are utilized. The main area where memory requirements must be drastically reduced is the equation solving area. The system matrix, when written in its original form, can occupy all the memory available and may leave no room for the code itself. For this reason, the frontal solution procedure described in Section 1.2.2 has been used exclusively for the pavement problem. Even though the frontal method minimizes the number of arithmetic operations required for the solution of the set of equations, the time taken up by the equation solving task is relatively long. Analysis duration time is approximately 3 hours for a typical pavement problem having about 1100 degrees of freedom and requiring the solution of about 6 equation sets (6 iterations). The long solution time is caused mainly by the excessive input/output operations required by the frontal method while writing the reduced equations one-by-one to disk and reading them, again one-by-one, for backsubstitution. This problem can be significantly alleviated by creating a small local buffer in which the reduced equations can be stored temporarily (Owen and Hinton, 1980). Once this buffer is full, the assembled equations are transferred to disk. The buffer is also used during backsubstitution to reduce the time required for the reading operation. While this feature is not

available in this code, its implementation is very simple and can result in significant time savings. Obviously, analysis duration time also depends on the efficiency of the rest of the code and on the computer that is being used.

Another modification is the division of the real adjustable-size array into two smaller-size arrays. This division has been selected so that the integer array index does not require more than two bytes of memory. Two important reasons for this selection are the use of Graphmatic and Plotmatic routines (Microcompatibles, 1983 and 1984) which accept 2-byte integers only and the use of the Microsoft Fortran Optimizing Compiler (Microsoft Corporation, 1987) which creates smaller and faster executable code for 2-byte arithmetic operations. All integer variables are then declared to be of type I2 by using the \$STORAGE metacommand or through the /4I2 compiler option.

The pre-processing additions to the code include the use of Grafmatic graphics library (Microcompatibles, 1983) to draw the finite element mesh on the screen so that node and element data can be checked prior to the analysis. Due to the low screen resolution, it is sometimes difficult to detect element connectivity errors for thin element layers in large models. For this reason, a zoom option has been added. Using this option, the user can "zoom" on any portion of the mesh by specifying the coordinates of the lower-left corner of the zoom window and its width and height. When all mesh-related errors are corrected, a plot of the mesh can be obtained through a batch job to the Hewlett-Packard 7470A plotter. The Plotmatic pen Plotter graphics library (Microcompatibles, 1984) is used for this purpose. Figures 3.21 and 3.22 show typical plots a pavement finite element mesh and a zoom on its asphaltic/concrete and base layers, respectively.

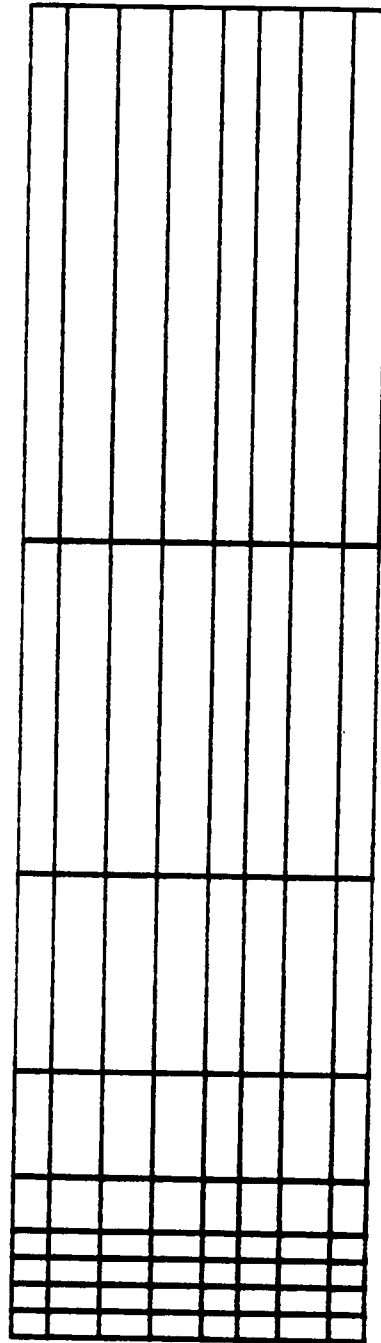
A1010A.DAT: TAC-18IN, TBSE-10IN, EAC-100KSI, GRAVEL BASE, STIFF SUBGRADE



PLOT OF ORIGINAL MESH

Figure 3.21 Plot of a Pavement Finite Element Mesh

11810A.DAT, TAC-10IN, TBSE-10IN, EAC-100KS1, GRAVEL BASE, STIFF SUBGRADE



ZOOM ON A PART OF THE MESH

Figure 3.22 Zoom on the Asphaltic Concrete and Base Layers

SUMMARY

A displacement-based finite element formulation using eight-noded isoparametric quadrilaterals has been used in the analysis of two non-linear problems in geomechanics. In the first problem, the improved VAX version, SSTIN, of the finite element code SSTIN(SEQ)-2D (Lightner and Desai, 1979 and Desai and Lightner, 1985) has been used in the analysis of an idealized residual soil-bedrock cavity system for the purpose of evaluating the stability of residual soils at the West Chestnut Ridge Site, Oak Ridge Reservation, Tennessee. The Sandler cap plasticity model has been chosen to represent the behavior of the residual soil. The iterative Newton-Raphson scheme has been adopted for the solution of the non-linear system of equations with the convergence criterion being a norm based on residual forces. A graphics package that uses Calcomp routines has been developed for drawing finite element meshes, displacement vectors, stress states, and deformed meshes. Several analyses have been performed for different combinations of cavity radius and thickness of residual soil overburden. The areal and vertical extent of yielded soil above the bedrock level have been selected as measures of distress in the system. These two damage indicators have been plotted versus cavity radius and versus cavity radius normalized with respect of overburden thickness. The results show that damage is more severe for large cavity radii or small overburden thicknesses. They also indicate that for high overburden thicknesses, the extent of damage is relatively insensitive to typical values of cavity radii.

In the second problem, the structural response of flexible pavement systems has been investigated. PCPAVAN, which is a micro-computer version of the

code that runs on an IBM PC-XT, has been developed exclusively for the analysis of pavement systems. The solution scheme is an iterative trial-and-error process that uses norms based on displacements and moduli values for convergence criteria. Due to the limited core memory available in micro-computers, the frontal method has been implemented for the solution of the linear systems of equations obtained at every iteration. The non-linear material models for the stress-hardening base course and the stress-softening subgrade have been incorporated into the code along with the Mohr-Coulomb stress modification procedure for the elimination of tensile stresses in the base course. Grafmatic and Plotmatic micro-computer graphics routines have been used to draw finite element meshes and magnified portions of meshes in order to check for errors in nodal coordinates and element connectivity. Many analyses have been performed for different combinations of asphaltic concrete (AC) thickness, AC modulus, base course thickness, and subgrade model parameters. A brief discussion of how these factors affect the stress-deformational response of flexible pavements is presented.

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APPENDIXES

APPENDIX A

LISTING AND VERIFICATION OF MOHRC. FOR:
A FORTRAN PROGRAM FOR THE MOHR-COULOMB STRESS
MODIFICATION PROCEDURE

LISTING AND VERIFICATION OF MOHRC.FOR: A FORTRAN PROGRAM
FOR MOHR-COULOMB STRESS MODIFICATION PROCEDURE

```

      PROGRAM MOHRC
C     MOHRC MODIFIES THE STRESS FIELD SO THAT THE MOHR-COULOMB FAILURE
C     CRITERION IS NOT VIOLATED
      IMPLICIT REAL*8 (A-H,O-Z)
      OPEN(UNIT=3,FILE='MOHRC.OUT',STATUS='NEW')
      WRITE(6,1005)
      READ *, SIGV,SIG1,SIG3,COH,PHI
      SIGX=SIG1+SIG3-SIGV
      TOXY=DSQRT(DABS(SIG1**2-SIG1*(SIGX+SIGV)+SIGX*SIGV))
      WRITE(3,1010) COH,PHI,SIGX,TOXY,SIGV,SIG1,SIG3
      WRITE(6,1010) COH,PHI,SIGX,TOXY,SIGV,SIG1,SIG3
      PI=3.1415927D0
      TPHI1=DTAN((45.0D0+PHI/2.0D0)*PI/180.0D0)
      TPHI2=DTAN((45.0D0-PHI/2.0D0)*PI/180.0D0)
      FAC1=TPHI1**2
      FAC2=2.0D0*COH*TPHI1
      FAC3=TPHI2**2
      FAC4=-2.0D0*COH*TPHI2
      SMX1=SIGV*FAC1+FAC2
      SMN3=SIGV*FAC3+FAC4
      IF (SMN3.LT.0.0D0) THEN
        SMN3=0.0D0
        IF (SIG3.LT.SMN3.OR.SIG3.GT.SIGV) THEN
          SIG3=0.0D0
          SPR1=FAC2
          GO TO 40
        ELSE
          GO TO 30
        ENDIF
      ELSE
        IF (SIG3.LT.SMN3.OR.SIG3.GT.SIGV) THEN
          SIG3=SMN3
          SIG1=SIGV
          GO TO 50
        ELSE
          GO TO 30
        ENDIF
      ENDIF
30    SPR1=SIG3*FAC1+FAC2
40    IF (SIG1.LT.SPR1) GO TO 50
      SIG1=SPR1
50    CONTINUE
      SIGX=SIG1+SIG3-SIGV
      TOXY=DSQRT(DABS(SIG1**2-SIG1*(SIGX+SIGV)+SIGX*SIGV))
      WRITE(6,1015) SIGV,SIGX,TOXY,SIG1,SIG3
      WRITE(3,1015) SIGV,SIGX,TOXY,SIG1,SIG3

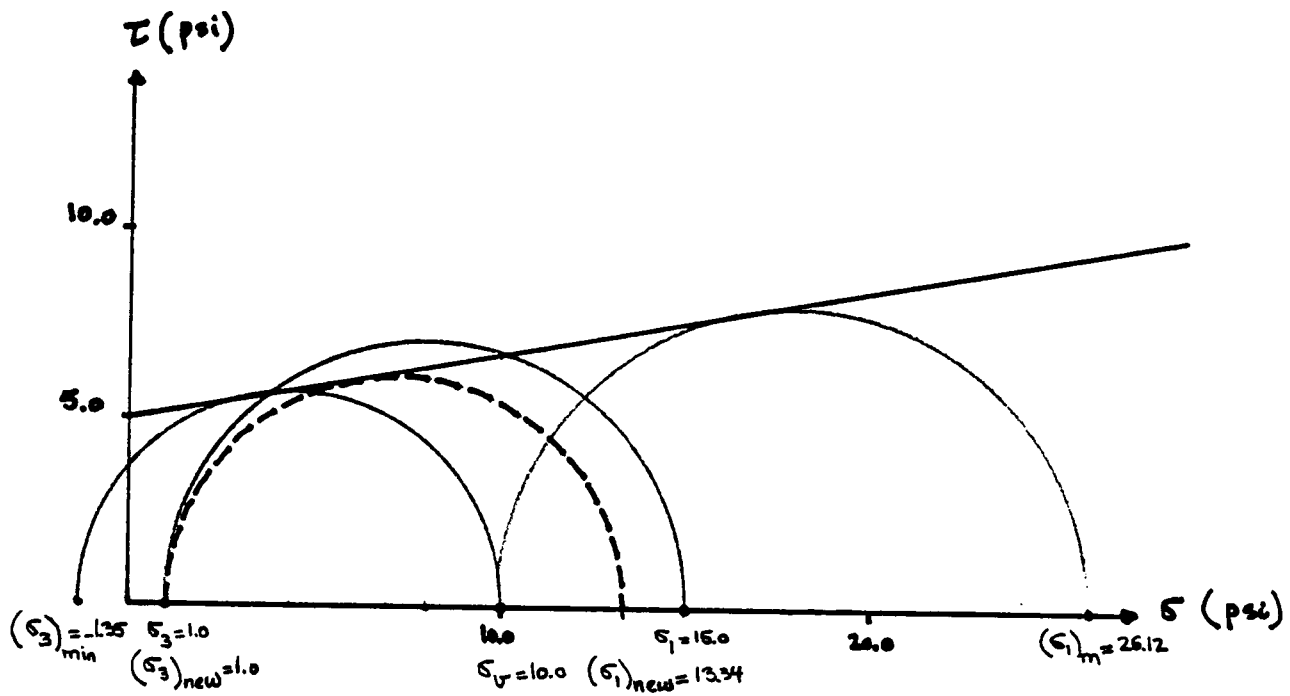
```

```

CLOSE(UNIT=3)
1005 FORMAT(/3X,'ENTER SIGV, SIG1, SIG3, C, AND PHI: ',%)
1010 FORMAT(/,3X,'MOHR-COULOMB STRESS MODIFICATION PROCEDURE:',/,3X,'=
1=====','/,5X,'INPUT INFORMATION
2N:',/,6X,'COHESION (PSI) :',D12.5,/,6X,'ANGLE OF INTERNAL FRICTION (DEGREES) :',D12.5,/,6X,'HORIZONTAL STRESS
3SIGX (PSI) :',D12.5,/,6X,'SHEAR STRESS TOXY (PSI)
45 :',D12.5,/,6X,'VERTICAL STRESS SIGV (PSI) :',D12.5,
6/,6X,'MAJOR PRINCIPAL STRESS SIG1 (PSI) :',D12.5,/,6X,'MINOR PR
7INCIPAL STRESS SIG3 (PSI) :',D12.5)
1015 FORMAT(/,5X,'OUTPUT OF PROCEDURE:',/,6X,'VERTICAL STRESS SIGV (PS
1I) :',D12.5,/,6X,'HORIZONTAL STRESS SIGX (PSI) :
2',D12.5,/,6X,'SHEAR STRESS TOXY (PSI) :',D12.5,/,6X,'
3MAJOR PRINCIPAL STRESS SIG1 (PSI) :',D12.5,/,6X,'MINOR PRINCIPA
4L STRESS SIG3 (PSI) :',D12.5)
END

```

$$\sigma_v = 10.0 \text{ psi} \quad \sigma_1 = 15.0 \text{ psi} \quad \sigma_3 = 1.0 \text{ psi} \quad \phi = 10^\circ \quad c = 5 \text{ psi}$$



MOHR-COULOMB STRESS MODIFICATION PROCEDURE:

=====

INPUT INFORMATION:

COHESION (PSI)	.50000D+01
ANGLE OF INTERNAL FRICTION (DEGREES)	.10000D+02
HORIZONTAL STRESS SIGX (PSI)	.60000D+01
VERTICAL STRESS SIGY (PSI)	.10000D+02
SHEAR STRESS TOXY (PSI)	.67082D+01
MAJOR PRINCIPAL STRESS SIG1 (PSI)	.15000D+02
MINOR PRINCIPAL STRESS SIG3 (PSI)	.10000D+01
ANGLE OF INCLINATION OF PRINCIPAL AXES (DEGREES) :	.36699D+02

OUTPUT OF PROCEDURE:

HORIZONTAL STRESS SIGX (PSI)	.43378D+01
VERTICAL STRESS SIGY (PSI)	.10000D+02
SHEAR STRESS TOXY (PSI)	.54809D+01
MAJOR PRINCIPAL STRESS SIG1 (PSI)	.13338D+02
MINOR PRINCIPAL STRESS SIG3 (PSI)	.10000D+01
ANGLE OF INCLINATION OF PRINCIPAL AXES (DEGREES) :	.36699D+02

MOHR-COULOMB STRESS MODIFICATION PROCEDURE:

=====

INPUT INFORMATION:

COHESION (PSI)	.50000D+01
ANGLE OF INTERNAL FRICTION (DEGREES)	.10000D+02
HORIZONTAL STRESS SIGX (PSI)	.43378D+01
VERTICAL STRESS SIGY (PSI)	.10000D+02
SHEAR STRESS TOXY (PSI)	.54809D+01
MAJOR PRINCIPAL STRESS SIG1 (PSI)	.13338D+02
MINOR PRINCIPAL STRESS SIG3 (PSI)	.99999D+00
ANGLE OF INCLINATION OF PRINCIPAL AXES (DEGREES) :	.31341D+02

OUTPUT OF PROCEDURE:

HORIZONTAL STRESS SIGX (PSI)	.43378D+01
VERTICAL STRESS SIGY (PSI)	.10000D+02
SHEAR STRESS TOXY (PSI)	.54809D+01
MAJOR PRINCIPAL STRESS SIG1 (PSI)	.13338D+02
MINOR PRINCIPAL STRESS SIG3 (PSI)	.99999D+00
ANGLE OF INCLINATION OF PRINCIPAL AXES (DEGREES) :	.31341D+02

APPENDIX B

SUMMARY OF FLEXIBLE PAVEMENT ANALYSES

SUMMARY OF FLEXIBLE PAVEMENT ANALYSES

LIST OF SYMBOLS

SYMBOL	DEFINITION	UNIT
Eri	Subgrade Breakpoint Modulus	Ksi
Eac	Modulus of the Asphaltic Concrete	Ksi
Tac	Thickness of Asphaltic Concrete Layer	Inches
Tbse	Thickness of Base Course	Inches
eac	Radial Strain at Bottom of AC Layer	Micro in/in
D0	Surface Deflection at Centerline	Mils
D1	Surface Deflection at 1 ft from Centerline	Mils
D2	Surface Deflection at 2 ft from Centerline	Mils
D3	Surface Deflection at 3 ft from Centerline	Mils
Ds	Subgrade Deflection at Centerline	Mils
ez	Vertical Strain at Top of Subgrade	Microin/in
Sz	Vertical Stress at Top of Subgrade	Micro in/in
Sd	Maximum Subgrade Deviator Stress	Psi

A1810D	12.34	1500.0	18.0	10.0	16.52	3.190	2.632	2.292	1.998	1.657	19.23	0.6785	0.2879
B0304A	7.680	100.0	3.0	4.0	672.3	44.69	17.01	5.447	2.586	35.61	294.6	23.82	18.02
B0306A	7.680	100.0	3.0	6.0	601.7	42.43	17.40	5.697	2.620	30.56	2319	19.83	15.11
B0310A	7.680	100.0	3.0	10.0	562.9	40.72	18.20	6.267	2.709	23.84	1560	14.64	10.98
B0604A	7.680	100.0	6.0	4.0	542.8	29.40	15.20	6.537	2.846	22.27	1405	13.52	10.35
B0606A	7.680	100.0	6.0	6.0	544.4	29.75	15.70	6.859	2.975	20.15	1170	12.14	9.157
B0610A	7.680	100.0	6.0	10.0	542.8	30.43	16.65	7.523	3.236	16.91	857.2	9.645	7.259
B1004A	7.680	100.0	10.0	4.0	339.7	20.80	12.02	6.655	3.565	14.10	658.1	7.917	5.985
B1006A	7.680	100.0	10.0	6.0	342.8	21.23	12.43	6.958	3.748	13.10	557.9	7.134	5.373
B1010A	7.680	100.0	10.0	10.0	351.1	22.15	13.25	7.573	4.162	11.31	413.1	5.693	4.380
B1804A	7.680	100.0	18.0	4.0	139.3	14.10	7.731	5.197	3.486	7.475	225.5	3.434	2.618
B1806A	7.680	100.0	18.0	6.0	141.9	14.41	8.023	5.439	3.676	7.051	196.9	3.010	2.313
B1810A	7.680	100.0	18.0	10.0	146.4	15.04	8.607	5.933	4.069	6.318	157.8	3.572	1.878
B0304B	7.680	500.0	3.0	4.0	405.7	31.99	16.43	6.208	2.609	26.63	1706	16.38	11.66
B0306B	7.680	500.0	3.0	6.0	392.6	31.93	16.84	6.491	2.619	23.95	1470	14.85	10.66
B0310B	7.680	500.0	3.0	10.0	374.9	32.05	17.62	7.062	2.797	19.78	1086	11.68	8.649
B0604B	7.680	500.0	6.0	4.0	210.7	17.41	12.09	6.818	3.624	14.21	567.0	7.923	5.359
B0606B	7.680	500.0	6.0	6.0	211.5	17.77	12.44	7.085	3.791	13.51	503.9	7.200	4.964
B0610B	7.680	500.0	6.0	10.0	214.3	18.65	13.25	7.706	4.198	11.77	404.9	5.966	4.250
B1004B	7.680	500.0	10.0	4.0	111.3	10.42	7.929	5.522	3.674	8.133	220.6	3.791	2.526
B1006B	7.680	500.0	10.0	6.0	112.5	10.70	8.199	5.750	3.856	7.705	196.6	3.432	2.277
B1010B	7.680	500.0	10.0	10.0	114.6	11.29	8.757	6.225	4.237	6.956	163.1	2.868	1.918
B1804B	7.680	500.0	18.0	4.0	40.34	5.486	4.024	3.218	2.555	3.694	69.01	1.346	0.7966
B1806B	7.680	500.0	18.0	6.0	40.75	5.645	4.18	3.364	2.691	3.513	61.31	1.231	0.7039
B1810B	7.680	500.0	18.0	10.0	41.44	5.959	4.486	3.655	2.962	3.192	50.94	1.051	0.5817
B0304C	7.680	1000.0	3.0	4.0	289.5	26.94	15.62	6.639	2.821	22.65	1227	13.78	9.313
B0306C	7.680	1000.0	3.0	6.0	282.6	27.03	15.94	6.890	2.914	20.70	1094	12.43	8.668
B0310C	7.680	1000.0	3.0	10.0	275.6	27.65	16.82	7.575	3.220	17.59	857.7	10.03	7.238
B0604C	7.680	1000.0	6.0	4.0	132.2	13.74	10.37	6.493	3.823	11.54	361.0	5.954	3.648
B0606C	7.680	1000.0	6.0	6.0	133.1	14.08	10.69	6.747	4.098	10.81	327.9	5.405	3.557
B0610C	7.680	1000.0	6.0	10.0	135.3	14.82	11.38	7.299	4.408	9.684	274.9	4.511	3.073
B1004C	7.680	1000.0	10.0	4.0	66.90	7.736	6.286	4.694	3.366	6.214	136.7	2.509	1.564
B1006C	7.680	1000.0	10.0	6.0	67.55	7.959	6.499	4.883	3.528	5.912	123.7	2.376	1.432
B1010C	7.680	1000.0	10.0	10.0	68.70	8.412	6.934	5.270	3.859	5.370	105.5	2.015	1.223
B1804C	7.680	1000.0	18.0	4.0	22.96	3.833	3.039	2.570	2.169	2.727	41.05	0.9671	0.4620
B1806C	7.680	1000.0	18.0	6.0	23.12	3.966	3.172	2.699	2.294	2.609	36.71	0.9373	0.4103
B1810C	7.680	1000.0	18.0	10.0	23.38	4.230	3.433	2.954	2.541	2.401	30.96	0.7289	0.3436
B0304D	7.680	1500.0	3.0	4.0	229.4	24.02	14.90	6.854	3.046	20.37	989.8	12.09	7.936
B0306D	7.680	1500.0	3.0	6.0	226.9	24.18	15.15	7.046	3.123	18.78	888.5	10.90	7.551
B0310D	7.680	1500.0	3.0	10.0	224.6	25.07	16.09	7.694	3.412	16.20	735.3	9.033	6.398
B0604D	7.680	1500.0	6.0	4.0	100.2	11.94	9.373	6.183	3.842	10.03	279.0	4.954	3.076
B0606D	7.680	1500.0	6.0	6.0	101.0	12.25	9.661	6.421	4.024	9.512	255.8	4.513	2.861
B0610D	7.680	1500.0	6.0	10.0	102.7	12.91	10.28	6.932	4.413	8.851	218.5	3.796	2.501
B1004D	7.680	1500.0	10.0	4.0	49.58	6.483	5.423	4.190	3.122	5.263	103.8	2.090	1.191
B1006D	7.680	1500.0	10.0	6.0	50.02	6.676	5.609	4.359	3.272	5.016	94.40	1.912	1.082
B1010D	7.680	1500.0	10.0	10.0	50.80	7.065	5.986	4.704	3.577	4.568	81.25	1.634	0.9325
B1804D	7.680	1500.0	18.0	4.0	16.48	3.188	2.629	2.289	1.995	2.330	30.74	0.7358	0.3397
B1806D	7.680	1500.0	18.0	6.0	16.56	3.313	2.754	2.412	2.116	2.239	27.66	0.6842	0.3032
B1810D	7.680	1500.0	18.0	10.0	16.71	3.563	3.002	2.657	2.356	2.082	23.62	0.6047	0.2566
C0304A	3.020	100.0	3.0	4.0	898.8	65.38	27.36	9.094	4.133	53.46	4691	16.02	11.46

PROBLEM TITLE	E _{ri} (ksi)	E _{ac} (ksi)	T _{ac} (in.)	T _{bsc} (in.)	e _{ac} mic in/in	D0 (mils)	D1 (mils)	D2 (mils)	D3 (mils)	Ds (mils)	e _z mic in/in	S _z (psi)	S _d (psi)
A0304A	12.34	100.0	3.0	4.0	586.3	35.25	12.37	3.860	1.885	26.93	2187	28.96	22.11
A0306A	12.34	100.0	3.0	6.0	559.2	34.70	13.04	4.103	1.893	23.40	1752	24.03	18.57
A0310A	12.34	100.0	3.0	10.0	552.1	35.13	14.34	4.464	1.907	18.43	1193	17.58	13.46
A0604A	12.34	100.0	6.0	4.0	512.3	24.79	11.77	4.685	1.953	17.50	1114	16.57	12.67
A0606A	12.34	100.0	6.0	6.0	514.8	25.30	12.33	4.951	2.012	15.83	927.2	14.42	10.97
A0610A	12.34	100.0	6.0	10.0	525.8	26.72	13.67	5.707	2.259	13.25	672.4	11.16	8.508
A1004A	12.34	100.0	10.0	4.0	319.7	18.03	9.659	5.036	2.548	11.32	535.9	9.316	7.021
A1006A	12.34	100.0	10.0	6.0	326.7	18.61	10.16	5.362	2.725	10.45	455.2	8.258	6.124
A1010A	12.34	100.0	10.0	10.0	338.3	19.83	11.22	6.062	3.116	9.020	339.1	6.588	4.931
A1804A	12.34	100.0	18.0	4.0	131.9	12.79	6.511	4.192	2.708	6.117	188.0	4.014	2.982
A1806A	12.34	100.0	18.0	6.0	135.5	13.16	6.848	4.461	2.908	5.741	162.4	3.588	2.663
A1810A	12.34	100.0	18.0	10.0	141.4	13.89	7.521	5.008	3.324	5.091	128.1	2.929	2.087
A0304B	12.34	500.0	3.0	4.0	369.4	26.19	12.47	4.393	1.840	20.79	1332	20.51	14.66
A0306B	12.34	500.0	3.0	6.0	360.9	26.47	12.97	4.581	1.836	18.73	1154	17.82	13.00
A0310B	12.34	500.0	3.0	10.0	356.9	27.61	14.22	5.156	1.861	15.45	855.1	13.71	10.29
A0604B	12.34	500.0	6.0	4.0	197.4	14.61	9.667	5.144	2.578	11.43	471.3	9.297	6.207
A0606B	12.34	500.0	6.0	6.0	200.2	15.11	10.11	5.433	2.730	10.64	413.1	8.337	5.661
A0610B	12.34	500.0	6.0	10.0	205.9	16.22	11.08	6.097	3.111	9.284	325.8	6.747	4.750
A1004B	12.34	500.0	10.0	4.0	65.6	8.977	6.589	4.422	2.834	6.667	185.1	4.465	2.890
A1006B	12.34	500.0	10.0	6.0	107.4	9.313	6.899	4.673	3.023	6.276	162.8	3.994	2.569
A1010B	12.34	500.0	10.0	10.0	110.5	10.01	7.542	5.197	3.418	5.600	132.8	3.278	2.133
A1804B	12.34	500.0	18.0	4.0	38.97	4.932	3.484	2.715	2.098	3.100	58.70	1.614	0.9293
A1806B	12.34	500.0	18.0	6.0	39.56	5.109	3.655	2.874	2.242	2.923	51.48	1.456	0.8106
A1810B	12.34	500.0	18.0	10.0	40.51	5.454	3.991	3.187	2.528	2.610	42.06	1.214	0.6596
A0304C	12.34	1000.0	3.0	4.0	264.2	22.11	12.03	4.763	1.945	17.85	985.0	16.74	11.37
A0306C	12.34	1000.0	3.0	6.0	261.5	22.55	12.52	5.001	1.988	16.32	873.5	14.82	10.39
A0310C	12.34	1000.0	3.0	10.0	262.2	23.83	13.72	5.694	2.219	13.80	675.7	11.66	8.512
A0604C	12.34	1000.0	6.0	4.0	124.5	11.57	8.424	5.022	2.810	9.263	301.9	6.979	4.411
A0606C	12.34	1000.0	6.0	6.0	126.3	12.00	8.802	5.303	2.997	8.699	269.8	6.263	4.034
A0610C	12.34	1000.0	6.0	10.0	129.8	12.89	9.609	5.904	3.397	7.707	222.7	5.120	3.428
A1004C	12.34	1000.0	10.0	4.0	63.86	6.713	5.313	3.852	2.676	5.153	115.5	3.113	1.835
A1006C	12.34	1000.0	10.0	6.0	64.80	6.971	5.557	4.063	2.848	4.871	103.2	2.800	1.638
A1010C	12.34	1000.0	10.0	10.0	66.43	7.493	6.054	4.493	3.204	4.371	86.57	2.327	1.377
A1804C	12.34	1000.0	18.0	4.0	22.42	3.407	2.619	2.165	1.782	2.268	34.85	1.077	0.5386
A1806C	12.34	1000.0	18.0	6.0	22.68	3.552	2.761	2.300	1.910	2.132	30.32	0.969	0.4651
A1810C	12.34	1000.0	18.0	10.0	23.03	3.828	3.035	2.566	2.165	1.935	25.43	0.8297	0.3861
A0304D	12.34	1500.0	3.0	4.0	211.0	19.79	11.58	4.945	2.080	16.13	805.7	14.61	9.610
A0306D	12.34	1500.0	3.0	6.0	211.7	20.36	12.09	5.226	2.166	14.93	726.3	13.10	8.956
A0310D	12.34	1500.0	3.0	10.0	213.7	21.61	13.21	5.863	2.394	12.75	579.0	10.44	7.478
A0604D	12.34	1500.0	6.0	4.0	94.68	10.09	7.679	4.852	2.881	8.161	233.8	5.826	3.531
A0606D	12.34	1500.0	6.0	6.0	96.02	10.46	8.017	5.113	3.066	7.691	211.6	5.243	3.240
A0610D	12.34	1500.0	6.0	10.0	98.63	11.25	8.738	5.676	3.467	6.859	177.6	4.319	2.783
A1004D	12.34	1500.0	10.0	4.0	47.52	5.652	4.625	3.481	2.519	4.391	88.00	2.500	1.384
A1006D	12.34	1500.0	10.0	6.0	48.15	5.873	4.837	3.669	2.680	4.156	79.02	2.260	1.241
A1010D	12.34	1500.0	10.0	10.0	49.26	6.317	5.264	4.050	3.008	3.735	66.94	1.892	1.054
A1804D	12.34	1500.0	18.0	4.0	16.17	2.801	2.245	1.913	1.629	1.914	25.93	0.8624	0.3940
A1806D	12.34	1500.0	18.0	6.0	16.32	2.933	2.376	2.041	1.752	1.808	22.72	0.7820	0.3422

D0604A	1.000	100.0	6.0	4.0	684.8	47.19	28.76	14.31	6.900	37.79	2284	7.201	5.567
D0606A	1.000	100.0	6.0	6.0	646.9	45.46	28.13	14.40	7.083	34.47	1930	8.060	6.159
D0610A	1.000	100.0	6.0	10.0	603.0	43.74	27.72	14.80	7.566	29.33	1389	6.779	5.225
D1004A	1.000	100.0	10.0	4.0	401.5	30.38	20.48	12.86	7.746	23.43	974.9	5.336	4.130
D1006A	1.000	100.0	10.0	6.0	394.9	30.37	20.57	13.03	7.926	21.98	851.2	4.895	3.886
D1010A	1.000	100.0	10.0	10.0	388.4	30.51	20.85	13.43	8.318	19.54	669.8	4.135	3.247
D1804A	1.000	100.0	18.0	4.0	159.5	18.28	11.69	8.598	6.268	11.73	326.8	2.243	1.806
D1806A	1.000	100.0	18.0	6.0	159.8	18.46	11.86	8.764	6.419	11.18	294.8	2.064	1.625
D1810A	1.000	100.0	18.0	10.0	161.1	18.82	12.22	9.101	6.726	10.22	246.7	1.778	1.354
D0304B	1.000	500.0	3.0	4.0	541.6	53.95	32.23	14.27	6.295	47.41	3133	9.384	5.504
D0306B	1.000	500.0	3.0	6.0	491.1	51.74	31.72	14.60	6.565	42.23	2464	8.874	6.172
D0310B	1.000	500.0	3.0	10.0	432.2	48.01	30.44	14.91	7.007	34.34	1801	8.053	5.987
D0604B	1.000	500.0	6.0	4.0	247.2	26.94	20.61	13.15	7.905	23.59	829.2	5.344	3.733
D0606B	1.000	500.0	6.0	6.0	244.1	26.97	20.71	13.32	8.079	22.32	760.2	4.930	3.533
D0610B	1.000	500.0	6.0	10.0	240.1	27.12	20.96	13.68	8.445	20.07	639.4	4.221	3.114
D1004B	1.000	500.0	10.0	4.0	126.0	15.03	12.30	9.262	6.707	12.79	315.5	2.463	1.710
D1006B	1.000	500.0	10.0	6.0	126.0	15.19	12.45	9.114	6.848	12.25	292.1	2.279	1.584
D1010B	1.000	500.0	10.0	10.0	126.2	15.52	12.78	9.731	7.141	11.28	254.5	1.980	1.381
D1804B	1.000	500.0	18.0	4.0	43.20	7.392	5.902	5.017	4.260	5.672	97.10	0.8629	0.5149
D1806B	1.000	500.0	18.0	6.0	43.31	7.52	6.029	5.142	4.382	5.487	89.08	0.8103	0.4703
D1810B	1.000	500.0	18.0	10.0	43.53	7.776	6.282	5.391	4.625	5.156	77.10	0.7258	0.4044
D0304C	1.000	1000.0	3.0	4.0	362.8	43.99	2.911	14.56	6.940	39.00	2240	8.090	4.932
D0306C	1.000	1000.0	3.0	6.0	342.2	42.95	28.83	14.75	7.140	36.19	1972	7.088	4.531
D0310C	1.000	1000.0	3.0	10.0	316.7	41.25	28.22	14.99	7.486	30.38	1376	7.019	5.192
D0604C	1.000	1000.0	6.0	4.0	152.7	20.99	17.06	11.82	7.742	18.68	527.0	3.985	2.651
D0606C	1.000	1000.0	6.0	6.0	152.0	21.12	17.20	11.98	7.895	17.82	494.8	3.698	2.531
D0610C	1.000	1000.0	6.0	10.0	151.1	21.43	17.54	12.34	8.228	16.28	431.9	3.205	2.282
D1004C	1.000	1000.0	10.0	4.0	70.50	10.61	9.124	7.303	5.669	9.223	185.7	1.596	0.9907
D1006C	1.000	1000.0	10.0	6.0	74.37	11.10	9.530	7.612	5.897	9.153	162.0	1.550	0.9727
D1010C	1.000	1000.0	10.0	10.0	74.58	11.40	9.822	7.393	6.162	8.505	161.4	1.367	0.8632
D1804C	1.000	1000.0	18.0	4.0	24.00	5.451	4.648	4.151	3.716	4.405	59.10	0.6120	0.3037
D1806C	1.000	1000.0	18.0	6.0	24.04	5.572	4.768	4.270	3.834	4.296	54.71	0.5821	0.2795
D1810C	1.000	1000.0	18.0	10.0	24.12	5.812	5.008	4.508	4.070	4.101	48.28	0.5341	0.2443
D0304D	1.000	1500.0	3.0	4.0	281.2	38.81	27.12	14.53	7.304	34.91	1819	7.010	4.096
D0306D	1.000	1500.0	3.0	6.0	271.6	38.28	26.95	14.64	7.448	32.62	1618	6.672	4.130
D0310D	1.000	1500.0	3.0	10.0	257.0	37.43	26.73	14.98	7.894	28.01	1158	6.370	4.643
D0604D	1.000	1500.0	6.0	4.0	114.9	18.06	15.09	10.89	7.453	16.17	403.4	3.507	2.133
D0606D	1.000	1500.0	6.0	6.0	114.6	18.20	15.23	11.04	7.597	15.49	381.8	3.074	2.046
D0610D	1.000	1500.0	6.0	10.0	114.3	18.53	15.57	11.38	7.909	14.25	341.0	2.670	1.848
D1004D	1.000	1500.0	10.0	4.0	54.28	9.115	7.979	6.540	5.223	7.976	146.3	1.320	0.7738
D1006D	1.000	1500.0	10.0	6.0	54.38	9.252	8.115	6.672	5.349	7.698	137.1	1.237	0.7250
D1010D	1.000	1500.0	10.0	10.0	54.54	9.528	8.388	6.936	5.603	7.194	122.5	1.101	0.6484
D1804D	1.000	1500.0	18.0	4.0	17.03	4.729	4.165	3.811	3.498	3.922	45.54	0.5192	0.2288
D1806D	1.000	1500.0	18.0	6.0	17.06	4.847	4.283	3.928	3.615	3.842	42.45	0.4977	0.2117
D1810D	1.000	1500.0	18.0	10.0	17.10	5.084	4.519	4.164	3.849	3.700	37.95	0.4633	0.1873

C0306A	3.020	100.0	3.0	6.0	786.9	58.42	26.55	9.443	4.245	43.70	3492	14.81	11.14
C0310A	3.020	100.0	3.0	10.0	590.2	51.98	26.22	10.39	4.516	34.21	2369	10.80	7.172
C0604A	3.020	100.0	6.0	4.0	626.4	39.19	22.51	10.60	4.913	31.35	1933	9.822	7.208
C0606A	3.020	100.0	6.0	6.0	601.1	38.33	22.40	10.82	5.071	28.26	1694	9.264	6.567
C0610A	3.020	100.0	6.0	10.0	576.0	37.67	22.60	11.34	5.427	23.77	1179	7.758	5.798
C1004A	3.020	100.0	10.0	4.0	375.5	26.09	16.64	9.968	5.737	19.28	847.3	6.225	4.791
C1006A	3.020	100.0	10.0	6.0	372.6	26.27	16.89	10.22	5.947	18.03	730.4	5.680	4.362
C1010A	3.020	100.0	10.0	10.0	371.4	26.77	17.45	10.78	6.381	15.96	564.3	4.759	3.688
C1804A	3.020	100.0	18.0	4.0	151.3	16.46	9.954	7.084	5.004	9.887	285.5	2.670	2.116
C1806A	3.020	100.0	18.0	6.0	152.5	16.69	10.18	7.283	5.174	9.392	253.7	2.441	1.894
C1810A	3.020	100.0	18.0	10.0	155.0	17.16	10.63	7.688	5.521	8.524	209.5	2.072	1.557
C0304B	3.020	500.0	3.0	4.0	491.6	44.13	24.83	10.32	4.417	37.09	2322	12.49	8.844
C0306B	3.020	500.0	3.0	6.0	449.8	42.53	24.63	10.60	4.571	33.88	2132	10.91	7.296
C0310B	3.020	500.0	3.0	10.0	410.3	40.35	24.18	11.10	4.917	27.58	1533	9.868	6.297
C0604B	3.020	500.0	6.0	4.0	232.2	22.69	16.76	10.23	5.878	19.42	722.9	6.230	4.288
C0606B	3.020	500.0	6.0	6.0	230.5	22.83	16.95	10.42	6.035	18.29	654.1	5.729	4.045
C0610A	3.020	500.0	6.0	10.0	229.2	23.31	17.47	10.92	6.431	16.37	539.9	4.856	3.540
C1004B	3.020	500.0	10.0	4.0	120.2	13.02	10.38	7.599	5.332	10.77	276.0	2.937	2.023
C1006B	3.020	500.0	10.0	6.0	120.6	13.22	10.58	7.782	5.492	10.27	252.0	2.697	1.851
C1010B	3.020	500.0	10.0	10.0	121.4	13.66	11.01	8.166	5.826	9.394	215.9	2.304	1.586
C1804B	3.020	500.0	18.0	4.0	42.18	6.525	5.044	4.188	3.464	4.779	85.51	1.024	0.6160
C1806B	3.020	500.0	18.0	6.0	42.38	6.663	5.181	4.320	3.591	4.596	77.47	0.9526	0.5533
C1810B	3.020	500.0	18.0	10.0	42.76	6.938	5.452	4.583	3.844	4.267	65.99	0.8386	0.4700
C0304C	3.020	1000.0	3.0	4.0	333.1	36.39	22.96	10.80	4.909	31.80	1689	9.930	6.400
C0306C	3.020	1000.0	3.0	6.0	317.6	35.67	22.84	11.01	5.080	28.94	1538	9.539	6.360
C0310C	3.020	1000.0	3.0	10.0	299.2	35.08	22.98	11.47	5.384	24.66	1172	8.041	5.778
C0604C	3.020	1000.0	6.0	4.0	144.4	17.77	14.07	9.394	5.915	15.48	459.3	4.670	3.079
C0606C	3.020	1000.0	6.0	6.0	144.3	17.99	14.28	9.596	6.087	14.72	426.1	4.304	2.906
C0610C	3.020	1000.0	6.0	10.0	144.5	18.48	14.77	10.04	6.458	13.55	365.7	3.681	2.575
C1004C	3.020	1000.0	10.0	4.0	71.45	9.559	8.035	6.245	4.685	8.082	171.2	1.899	1.227
C1006C	3.020	1000.0	10.0	6.0	71.74	9.732	8.203	6.402	4.828	7.048	158.0	1.858	1.144
C1010C	3.020	1000.0	10.0	10.0	72.28	10.09	8.549	6.724	5.119	7.142	140.0	1.599	0.9997
C1804C	3.020	1000.0	18.0	4.0	23.64	4.689	3.889	3.402	2.978	3.623	51.43	0.709	0.3601
C1806C	3.020	1000.0	18.0	6.0	23.72	4.814	4.013	3.524	3.098	3.510	46.98	0.6677	0.3268
C1810C	3.020	1000.0	18.0	10.0	23.86	5.061	4.259	3.767	3.338	3.310	40.74	0.601	0.2809
C0304D	3.020	1500.0	3.0	4.0	260.3	32.16	21.52	10.88	5.213	28.39	1360	8.824	5.500
C0306D	3.020	1500.0	3.0	6.0	253.8	31.96	21.56	11.06	5.344	26.19	1223	8.685	5.872
C0310D	3.020	1500.0	3.0	10.0	243.4	31.81	21.82	11.51	5.656	22.70	981.3	7.302	5.249
C0604D	3.020	1500.0	6.0	4.0	109.0	15.36	12.55	8.768	5.790	13.47	353.6	2.887	2.475
C0606D	3.020	1500.0	6.0	6.0	109.1	15.57	12.76	8.957	5.951	12.86	330.9	3.591	2.348
C0610D	3.020	1500.0	6.0	10.0	109.6	16.05	13.22	9.374	6.301	11.76	289.2	3.092	2.105
C1004D	3.020	1500.0	10.0	4.0	52.53	7.964	6.856	5.494	4.270	6.793	128.9	1.582	0.9244
C1006D	3.020	1500.0	10.0	6.0	52.74	8.120	7.008	5.638	4.405	6.528	119.5	1.470	0.8563
C1010D	3.020	1500.0	10.0	10.0	53.11	8.436	7.319	5.932	4.678	6.044	105.2	1.290	0.7549
C1804D	3.020	1500.0	18.0	4.0	16.85	3.994	3.432	3.082	2.776	3.170	39.10	0.5899	0.2682
C1806D	3.020	1500.0	18.0	6.0	16.89	4.114	3.552	3.201	2.894	3.086	35.96	0.5596	0.2448
C1810D	3.020	1500.0	18.0	10.0	16.96	4.335	3.792	3.440	3.130	2.938	31.59	0.5116	0.2128
D0304A	1.000	100.0	3.0	4.0	1088	83.51	37.35	12.83	5.624	69.71	6751	12.62	6.210
D0306A	1.000	100.0	3.0	6.0	618.1	72.76	34.96	13.23	5.827	55.03	4140	15.50	6.210
D0310A	1.000	100.0	3.0	10.0	618.6	61.68	33.24	14.18	6.257	41.52	2744	9.308	6.210

APPENDIX C

USER MANUAL FOR THE GENERAL VERSION OF THE CODE SSTIN

PREFACE

SSTIN is a modified version of the computer code SSTIN(SEQ)-2D written at by C. S. Desai and J. Lightner. The purpose of the code is the application of the finite element method (FEM) in the non-linear analysis of two-dimensional soil-structure interaction problems including simulation of construction sequences such as insitu stresses, dewatering, embankment, excavation and installation of supports. Also, this code allows for interface and joint behavior by using the thin-layer element concept. The new version of the code has a graphics package that enables the user to verify the mesh data by drawing the finite element mesh before running any analyses. The user can also obtain drawings of the displacement vectors, the distribution of the states of stress throughout the mesh, and the deformed mesh. All graphs are performed by calling appropriate CALCOMP subroutines made available by the University of Tennessee Computing Center through its VAXCluster system.

I. PROBLEM INFORMATION (IN MASTER)
(10A8) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
TITLE OF PROBLEM	TITLE	1-80

NOTE: MULTIPLE JOBS MAY BE RUN BY STACKING THE DATA.
A BLANK CARD MUST BE INSERTED AT THE END OF A
JOB TO TERMINATE EXECUTION.

II. PROBLEM PARAMETERS (IN DATAIN)
(8I5,3E10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
JOB NUMBER	JOB	1-5
TOTAL NO. OF NODE POINTS	NNP	6-10
TOTAL NUMBER OF ELEMENTS	NEL	11-15
NUMBER OF MATERIAL TYPES	NMAT	16-20
CONSTITUTIVE MODEL TYPE	MNLIN	21-25
1 = LINEAR ELASTIC		
2 = VARIABLE MODULI		
3 = DRUCKER-PRAGER		
4 = SANDLER-CAP		

NOTE: IF MORE THAN ONE TYPE IS USED, INSERT HERE THE
HIGHER NUMBER. SUBSEQUENT MATERIAL PROPERTIES
DATA WILL TAKE CARE OF THE OTHER TYPES.

NUMBER OF GLOBAL LOAD INCREMENTS	NINCR	26-30
MAXIMUM NO. OF ITERATIONS	NITER	31-35
PROBLEM TYPE	NOPT	36-40
0 = AXISYMMETRIC		
1 = PLANE STRAIN		
2 = PLANE STRESS		
UNIT WEIGHT OF WATER	ROWAT	41-50
ATMOSPHERIC PRESSURE ONLY NEEDED FOR VARIABLE MODULI MODEL	ATMC	51-60
THICKNESS OF ELEMENTS	THICK	61-70

DEFAULT = 1.00

III. TAPE OUTPUT AND GRAPHICS INFORMATION
(I5,4(2X,I1,I2),I5,2E10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
TAPE OUTPUT FLAG 0 = DONT WRITE 1 = WRITE	IWRITE	1-5
OPTION FOR DRAWING MESH 0 = DONT DRAW 1 = DRAW	IMESH	8
LIMITER ON GLOBAL LOAD INCREMENTS 1 = ALL LOAD INCREMENTS 2 = EVERY OTHER INCREMENT 3 = ETC LAST INCR. ALWAYS INCLUDED	LMESH	9-10
OPTION TO PLOT DISPL. VECTORS 0 = DONT PLOT 1 = PLOT	IDVECT	13
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS 2 = EVERY OTHER LOAD STEP 3 = ETC LAST STEP ALWAYS INCLUDED	LDVECT	14-15
OPTION FOR STRESS STATES DISTRIBUTION 0 = DONT DRAW 1 = DRAW	ISTRST	18
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS 2 = EVERY OTHER LOAD STEP 3 = ETC LAST STEP ALWAYS INCLUDED	LSTRST	19-20
OPTION FOR DRAWING DEFORMED MESH 0 = DONT DRAW 1 = DRAW	IDMESH	23
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS 2 = EVERY OTHER LOAD STEP 3 = ETC LAST STEP ALWAYS INCLUDED	LDMESH	24-25
ZOOM OPTION	IZOOM	26-30

1 = ZOOM

NOTE: ZOOM OPTION IS NOT AVAILABLE IN THE CURRENT
VERSION OF THE CODE.

SIZE OF GRAPH	Gsize	31-40
Y-AXIS HEIGHT IN INCHES		
DEFAULT = 11.0 IN.		
MAXIMUM = 30.0 IN.		

DISPL. MAGNIFIACATION FACTOR DMAG 41-50

III-A. ZOOM INFORMATION (NOT NEEDED IF IZOOM = 0)
(4E10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
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COORDINATES OF LOWERLEFT CORNER OF ZOOM RECTANGLE		
X-COORDINATE	XORZM	1-10
Y-COORDINATE	YORZM	11-20

DIMENSIONS OF ZOOM RECTANGLE		
WIDTH	WZOOM	21-30
HEIGHT	HZOOM	31-40

IV. MATERIAL PROPERTIES (IN DATAIN)
(2I5,4E10.3/5E10.3/5E10.3) (3 CARDS/MATERIAL)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
---------------	----------	-----------

[CARD 1]

```

CONSTITUTIVE MODEL TYPE                                JCODE(I)  1-5
  0 = LINEAR ELASTIC
  1 = VARIABLE MODULI
  2 = DRUCKERPRAGER
  3 = SANDLERCAP
  4 = LINEAR INTERFACE
  5 = HYPERBOLIC INTERFACE

```

```

ELEMENT TYPE                                IELTYP(I) 6-10
 1 = SOIL
 2 = STRUCTURE
 3 = INTERFACE
 4 = 3-NODE BAR
 5 = 2-NODE BAR

```

YOUNG'S MODULUS FOR E (I) 11-20
SOLID AND BAR ELEMENTS

POISSON'S RATIO	PR(I)	21-30
FOR SOLID ELEMENTS OR		
AREA FOR BAR ELEMENTS		

UNIT WEIGHT	RO(I)	31-40
COEFFICIENT OF LATERAL EARTH PRESSURE	COER(I)	41-50

[CARD 2]

V1	PHI(I)	1-10
V2	CIN(I)	11-20
V3	PHJ(I)	21-30
V4	FR(I)	31-40
V5	EXPO(I)	41-50

[CARD 3]

V6	COFK(I)	1-10
V7	COFKR(I)	11-20
V8	GG(I)	21-30
V9	DD(I)	31-40
V10	FF(I)	41-50

NOTE: THE VARIABLE V1-V10 ON CARDS 2 AND 3 ARE DEFINED
AS FOLLOWS DEPENDING ON THE CONSTITUTIVE MODEL
USED.

1. LINEAR ELASTIC

V1 -- V10 NOT USED

2. VARIABLE MODULI - SOLID ELEMENT

V1 = ANGLE OF INTERNAL FRICTION
V2 = COHESION
V3 = TENSION CUTOFF
V4 = FAILURE RATIO
V5 = EXPONENT
V6 = LOADING FACTOR
V7 = UNLOADING FACTOR
V8 = POISSON PARAMETER
V9 = POISSON PARAMETER
V10 = POISSON PARAMETER

3. DRUCKER-PRAGER MODEL

V1 = ANGLE OF INTERNAL FRICTION
V2 = COHESION
V3 = TENSION CUTOFF
V4 -- V10 NOT USED

4. SANDLER CAP MODEL

V1 = A
V2 = B
V3 = TENSION CUTOFF
V4 = C
V5 = D
V6 = R
V7 = W

V8 = PRECONSOLIDATION PRESSURE
 V9 -- V10 NOT USED

5. LINEAR INTERFACE

V1 = BLANK
 V2 = G
 V8 -- V10 NOT USED

6. HYPERBOLIC INTERFACE

V1 = PHI
 V2 = COHESION
 V3 = TENSION CUTOFF
 V4 = FAILURE RATIO
 V5 = EXPONENT
 V6 = LOADING FACTOR
 V7 = G
 V8 -- V10 NOT USED

V. NODAL POINT DATA (IN DATAIN)

(I5,3X,2I1,4E10.3,T80,I1) (1 CARD/NODAL POINT)*

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
NODE POINT NUMBER	M	1-5
FIXITY CODE IN X DIRECTION 0 = FREE 1 = FIXED	IA(IIFIX	9
FIXITY CODE IN Y DIRECTION 0 = FREE 1 = FIXED	IA(IIFIX	10
X COORDINATE	A(IX	11-20
Y COORDINATE	A(IY	21-30
WATER HEAD	A(IUD	31-40
CHANGE IN WATER HEAD	A(IUT	41-50
DATA GENERATION CODE 1 = GENERATED FIXITY CODES SAME AS LAST ONE 0 = GENERATED FIXITY CODES ARE SET TO ZERO (FREE)	NCODE	80

* AUTOMATIC GENERATION OF NODES IS POSSIBLE. NODES MUST BE EQUIDISTANT AND ON A STRAIGHT LINE. INPUT FIRST AND LAST NODES. FIXITY CODE IS SET TO ZERO UNLESS THE LAST NODE CARD DATA GENERATION CODE IS SET TO ONE. THEN THE FIXITY CODE IS SET THE SAME AS THE LAST NODE.

VI. ELEMENT DATA (IN DATAIN)

(12I5,12X,8I1) (1 CARD/ELEMENT)**

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
ELEMENT NUMBER	M	1-5
NODE I	IA(IIE	6-10
NODE J	IA(IIE	11-15
NODE K	IA(IIE	16-20
NODE L	IA(IIE	21-25
NODE M	IA(IIE	26-30
NODE N	IA(IIE	31-35
NODE O	IA(IIE	36-40
NODE P	IA(IIE	41-45
MATERIAL TYPE NUMBER	IA(IIE	46-50
INTEGRATION TYPE	IA(IIE	51-55
0 = 2X2 POINT		
1 = 3X3 POINT		
FLAG FOR MIDPOINT NODE	ICOR	56-60
GENERATION		
0 = GENERATE		
1 = DONT GENERATE		
ELEMENT GENERATION DATA	I1	73
	I2	74
	I3	75
	I4	76
	I5	77
	I6	78
	I7	79
	I8	80

** AUTOMATIC GENERATION OF ELEMENTS IS POSSIBLE. INPUT THE FIRST ELEMENT OF A PATTERN AND THE FIRST ELEMENT TO BREAK THE PATTERN. IN COLUMNS 73 TO 80, PLACE NUMBERS TO BE ADDED TO PREVIOUS ELEMENT'S NODAL VALUES TO OBTAIN NEXT ELEMENT'S VALUES. PLACE THIS DATA ON THE CARD WHICH BREAKS THE PATTERN, NOT THE FIRST CARD IN THE PATTERN.

REFERRING TO FIG. 1, TO GENERATE AN ELEMENT BESIDE THE ONE SHOWN, LOOK AT NODE I AND THE CORRESPONDING NODE IN THE NEXT ELEMENT. TAKE THE DIFFERENCE BETWEEN THEIR GLOBAL NODE NUMBERS. PLACE THIS NUMBER IN COLUMN 73 AS THE PATTERN CODE. CONTINUE FOR EACH NODE J,K,L,M,N,O,P AND COLUMNS 74,75,76,77,78,79,80 RESPECTIVELY.

FIG. 1: 2D ISOPARAMETRIC ELEMENT

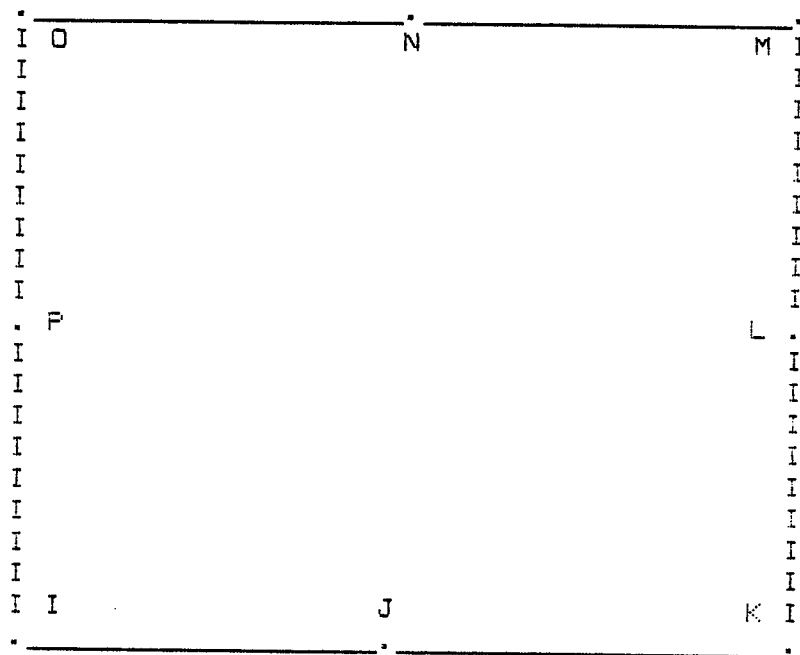
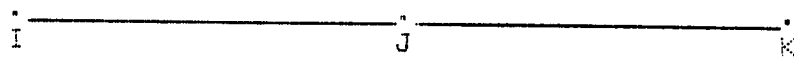


FIG. 2: 2-NODE BAR ELEMENT



FIG. 3: 3-NODE BAR ELEMENT



VII. OUTPUT CONTROL INFORMATION (IN DATAIN)
(A4/16I5) (AS MANY CARDS AS NEEDED)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
FLAG FOR OUTPUT CONTROL	AA	1-4
AA = ALL : OUTPUT PRINTED FOR ALL NODES AND ELEMENTS		
AA = DISP: OUTPUT FOR ALL ELEMENTS BUT LIMITED NODES		
AA = STRS: OUTPUT FOR ALL NODES BUT LIMITED ELEMENTS		
AA = BOTH: OUTPUT FOR LIMITED ELEMENTS AND NODES		

1. LIMITED NODES OUTPUT
(NEEDED IF AA EQUALS DISP OR BOTH)

NUMBER OF NODES FOR WHICH OUTPUT IS WANTED	NDSPRT	1-5
NODES FOR WHICH OUTPUT IS WANTED	IDSPRT(1)	1-5
	IDSPRT(2)	6-10
	IDSPRT(3)	11-15
	IDSPRT(4)	16-20, ETC

2. LIMITED ELEMENTS OUTPUT
(NEEDED IF AA EQUALS STRS OR BOTH)

NUMBER OF ELEMENTS FOR WHICH OUTPUT IS WANTED	NSTPRT	1-5
ELEMENTS FOR WHICH OUTPUT IS WANTED	ISTPRT(1)	1-5
	ISTPRT(2)	6-10
	ISTRPT(3)	11-15
	ISTRPT(4)	16-20, ETC

**** PARTS IX. TO XI. ARE REPEATED FOR EACH LOAD INCREMENT

VIII. INCREMENT CONTROL DATA (IN MASTER)
(7I5, 1X, 5I1) (1 CARD/LOAD INCREMENT)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
SEQUENCE TYPE	NSEQ	1-5
0 = INSITU LOADING		
1 = DEWATERING		
2 = EXCAVATING		
3 = EMBANKMENT		
4 = SURFACE AND/OR POINT LOADS ONLY.		
5 = INCREMENTAL INSITU		

NO. OF SURFACE LOAD CARDS (1 CARD/LOADED ELEMENT)	NSLC	6-10
NO. OF CONCENTRATED LOADS (LOADS AT NODES ONLY)	NFORCE	11-15
MESH MODIFICATION CODE 0 = MESH IS O.K. 1 = CHANGE MESH (DELETE) 2 = CHANGE MESH (ADD)	NMESH	16-20
NO. OF LOAD INCREMENTS FOR THIS SEQUENCE TO BE DIVIDE INTO (DEFAULT = 1)	NSTEPS	21-25
OPTION FOR STRESS TRANSFER 1 = STRESS TRANSFER 0 = NO STRESS TRANSFER	ISTER	26-30
NUMBER OF NODES WITH SPE- CIFIED NODAL QUANTITIES	NDISP	31-35
FLAG FOR OUTPUT FOR THIS SEQUENCE 0 = OUTPUT 1 = NO OUTPUT	IPR(1)	37
FLAG FOR OUTPUT OF ITER- ATIONS 0 = NO OUTPUT 1 = OUTPUT	IPR(2)	38
LIMITER FOR SEQUENCE OUTPUT 1 = ALL INCREMENT OUTPUT 2 = EVERY SECOND INCREMENT 3 = EVERY THIRD INCREMENT 4 = ETC LAST INCR. ALWAYS OUTPUT	IPR(3)	39
NOTE: IF IPR(1) = 1 THEN IPR(2) AND IPR(3) ARE NULLIFIED.		
SOLUTION METHOD 0 = FRONTAL 1 = BANDED	IPR(4)	40
FLAG FOR CALCULATING STRESSES AT SPECIFIED NODAL POINTS 0 = NO 1 = YES	KSTPLT	41

IX.-A. MESH MODIFICATION DATA (IN NODEL)
(NOT NEEDED IF MESH IS NOT TO BE CHANGED)

1. CONTROL INFORMATION
(315) (1 CARD/MESH CHANGE)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
FLAG FOR ELEMENTS ADDED OR DELETED 0 = NO 1 = YES	NIAELM	1-5
FLAG FOR NODES ADDED OR DELETED 0 = NO 1 = YES	NONOD	6-10
FLAG FOR ELEMENTS WHICH HAVE CHANGES IN MATE- RIAL PROPERTIES 0 = NO 1 = YES	NUMELC	11-15

2. ELEMENT DELETION OR ADDITION DATA (IN NODEL)
(15,1X,A4) (AS MANY CARDS AS NEEDED)***
(NOT NEEDED IF NIAELM = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ELEMENT NUMBER ADDED OR DELETED	NELL	1-5
KEY A BLANK = NO GENERATE GEN = GENERATE LAST = LAST ELEMENT	COD	7-10

3. NODAL DELETION OR ADDITION DATA (IN NODEL)
(15,3X,2I1,1X,A4) (AS MANY CARDS AS NEEDED)***
(NOT NEEDED IF NONOD = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE NUMBER TO BE ADDED OR DELETED	NODE	1-5
FIXITY CODE FOR X DEGREE OF FREEDOM 0 = ADDED 1 = DELETED	IXX	9

FIXITY CODE FOR Y	IYY	10
DEGREE OF FREEDOM		
0 = ADDED		
1 = DELETED		

KEY	COD	12-15
A BLANK = NO GENERATE		
GEN = GENERATE		
LAST = LAST NODE		

4. ELEMENT CHANGE DATA (IN NODEL)
 (2I5,1X,A4) (AS MANY CARDS AS NEEDED)***
 (NOT NEEDED IF NUMELC = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ELEMENT NUMBER TO HAVE MATERIAL NUMBER CHANGED	NELL	1-5
NEW MATERIAL NUMBER	MT	6-10
KEY	COD	12-15
A BLANK = NO GENERATE		
GEN = GENERATE		
LAST = LAST ELEMENT		

*** ELEMENTS OR NODES IN NUMERICAL ORDER MAY BE
 GENERATED BY SPECIFYING FIRST ELEMENT OR NODE IN A
 STRING WITH KEY BEING BLANK AND THE LAST ELEMENT
 OR NODE OF STRING WITH KEY BEING GEN OR LAST.

X. SEQUENCING DATA FOR EMBANKMENT, EXCAVATION, OR INITIAL BAR STRESS SEQUENCES

- A. FOR EMBANKMENTS, THE MESH CHANGE DATA FROM IX.-A.
MUST BE INPUT HERE.
- B. FOR EXCAVATIONS, THE MESH CHANGE DATA FROM IX.-A.
MUST BE INPUT HERE.
- C. FOR INITIAL BAR STRESSES, THE FOLLOWING DATA IS
INPUT HERE.
(I5 / I5,E10.3)

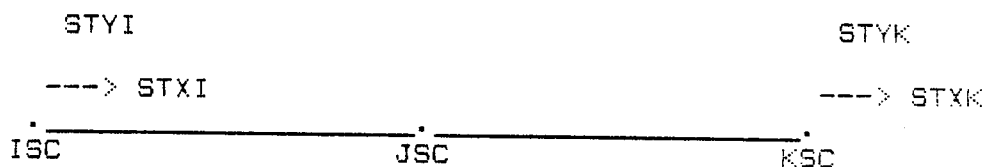
<DESCRIPTION>	<SYMBOL>	<COLUMN>
NO. OF ELEMENTS FOR WHICH STRESS IS SPECIFIED		1-5
NOTE: THIS CAN BE ADDED.		

ELEMENT NUMBER	1-5
INITIAL STRESS	6-15

X. SURFACE LOAD DATA (IN MASTER)
 (3I5,4E10.3) (1 CARD/SURFACE LOAD)
 (NOT NEEDED IF NO SURFACE LOADS)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ISC	ISC(I)	1-5
JSC	JSC(I)	6-10
KSC	KSC(I)	11-15
STXI	STXI(I)	16-25
STXK	STXK(I)	26-35
STYI	STYI(I)	36-45
STYK	STYK(I)	46-55

FIG. 4 SURFACE LOADING



XI. CONCENTRATED LOADS DATA (IN MASTER)
 (I5,2E10.3) (1 CARD/LOAD)
 (NOT NEEDED IF NFORCE = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE WHERE LOAD IS APPLIED	NODE	1-5
X FORCE	XFORC	6-15
Y FORCE	YFORC	16-25

XII. SPECIFIED DISPLACEMENTS FOR NODES OTHER THAN
 BOUNDARY CONDITION (IN MASTER)
 (I5,2E10.3) (AS MANY CAEDS AS NDISP)
 (NOT NEEDED IF NDISP = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE WHERE DISPLACEMENT IS APPLIED	NODE	1-5
X DISPLACEMENT	XDISP	6-15
Y DISPLACEMENT	YDISP	16-25

XIII. NODES AT WHICH STRESSES ARE REQUIRED
 (I5 / 2I5) (NOT NEEDED IF KSTPLT=0)

NUMBER OF NODES	NNPST	1-5
ELEMENT NUMBER	M	1-5
NODE NUMBER	NODE	6-10

NOTE: NODE IS AN INTEGER 1 THROUGH 8 DETERMINED BY
 STARTING AT THE LOWER LEFT CORNER OF THE ELEMENT
 (NODE 1) AND NUMBERING IN INCREASING ORDER
 COUNTERCLOCKWISE.

APPENDIX D

**USER MANUAL FOR THE PAVEMENT VERSION
OF THE CODE PCPAVAN**

PREFACE

PCPAVAN is a displacement-based finite element code for the analysis of flexible pavement systems. Any layer in the system can have any one of the following material behavior models:

- 1- Linear elastic
- 2- Hardenig model (for gravel/stone)
- 3- Bilinear softening (subgrade)
- 4- Quadratic softening (subgrade)

The code uses an eight-noded isoparametric element with four or nine integration points. The frontal routine is selected for the solution of the resulting system of simultaneous equations because of its efficiency and small memory requirement.

PCPAVAN runs on the IBM PC-XT microcomputer with 640 kilobytes of memory. Grafmatic subroutines are used to draw the deformed mesh on the screen for error checking purposes; and Plotmatic subroutines are used to create plots for the HP7470A plotter.

I. PROBLEM INFORMATION (IN MASTER)
(10A8) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
TITLE OF PROBLEM	TITLE	1-80

NOTE: MULTIPLE JOBS MAY BE RUN BY STACKING THE DATA.
A BLANK CARD MUST BE INSERTED AT THE END OF A
JOB TO TERMINATE EXECUTION.

II. PROBLEM PARAMETERS (IN DATAIN)
(7I5,1D10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
JOB NUMBER	JOBNO	1-5
TOTAL NO. OF NODE POINTS	NNP	6-10
TOTAL NUMBER OF ELEMENTS	NEL	11-15
NUMBER OF MATERIAL TYPES	NMAT	16-20

NOTE: IF MORE THAN ONE TYPE IS USED, INSERT HERE THE
HIGHER NUMBER. SUBSEQUENT MATERIAL PROPERTIES
DATA WILL TAKE CARE OF THE OTHER TYPES.

NUMBER OF LOADING CASES	LCASE	26-30
MAXIMUM NO. OF ITERATIONS	NITER	31-35
PROBLEM TYPE	NOPT	36-40
0 = AXISYMMETRIC		
1 = PLANE STRAIN		
2 = PLANE STRESS		

THICKNESS OF ELEMENTS	THICK	61-70
DEFAULT = 1.00		

III. TAPE OUTPUT AND GRAPHICS INFORMATION
(I5,4(2X,I1,I2),I5,2D10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
TAPE OUTPUT FLAG	IWRITE	1-5
0 = DONT WRITE		
1 = WRITE		

OPTION FOR DRAWING MESH 0 = DONT DRAW 1 = DRAW	IMESH	7
OPTION FOR SCREEN DUMP 0 = NO DUMP 1 = DUMP	IMESD	8
LIMITER ON SEQUENCES 1 = ALL LOAD SEQUENCES 2 = EVERY OTHER SEQUENCES 3 = ETC LAST INCR. ALWAYS INCLUDED	LMESH	9-10
OPTION TO PLOT DISPL. VECTORS 0 = DONT PLOT 1 = PLOT	IDVECT	12
OPTION FOR SCREEN DUMP 0 = NO DUMP 1 = DUMP	IVECD	13
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS 2 = EVERY OTHER LOAD STEP 3 = ETC LAST STEP ALWAYS INCLUDED	LDVECT	14-15
OPTION FOR STRESS STATES DISTRIBUTION 0 = DONT DRAW 1 = DRAW	ISTRST	17
OPTION FOR SCREEN DUMP 0 = NO DUMP 1 = DUMP	ISTRD	18
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS 2 = EVERY OTHER LOAD STEP 3 = ETC LAST STEP ALWAYS INCLUDED	LSTRST	19-20
OPTION FOR DRAWING DEFORMED MESH 0 = DONT DRAW 1 = DRAW	IDMESH	22
OPTION FOR SCREEN DUMP 0 = NO DUMP 1 = DUMP	IDEFD	23
LIMITER ON LOAD STEPS 1 = ALL LOAD STEPS	LDMESH	24-25

2 = EVERY OTHER LOAD STEP
 3 = ETC
 LAST STEP ALWAYS INCLUDED

ZOOM OPTION	IZOOM	26-30
0 = DONT ZOOM		
1 = ZOOM		
SIZE OF GRAPH	GSize	31-40
Y-AXIS HEIGHT IN INCHES		
DEFAULT = 11.0 IN.		
MAXIMUM = 30.0 IN.		
DISPL. MAGNIFIACATION FACTOR	DMAG	41-50

III-A. ZOOM INFORMATION (NOT NEEDED IF IZOOM = 0)
 (4D10.3) (1 CARD)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
COORDINATES OF LOWERLEFT CORNER OF ZOOM RECTANGLE		
X-COORDINATE	XORZM	1-10
Y-COORDINATE	YORZM	11-20
DIMENSIONS OF ZOOM RECTANGLE		
WIDTH	WZOOM	21-30
HEIGHT	HZOOM	31-40

IV. MATERIAL PROPERTIES (IN DATAIN)
 (2I5/5D10.3/5D10.3) (3 CARDS/MATERIAL)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
---------------	----------	-----------

[CARD 1]

CONSTITUTIVE MODEL TYPE	JCODE(I)	1-5
0 = LINEAR ELASTIC		
1 = GRAVEL/STONE BASE		
2 = BILINEAR SUBGRADE		
3 = QUADRATIC SUBGRADE		
4 = LINEAR INTERFACE		
5 = HYPERBOLIC INTERFACE		
ELEMENT TYPE	IELTYP(I)	6-10
1 = SOIL		
2 = STRUCTURE		
3 = INTERFACE		
4 = 3-NODE BAR		
5 = 2-NODE BAR		

[CARD 2]

MATERIAL MODEL PARAMETERS	PRMT(MT,1)	1-10
	PRMT(MT,2)	11-20
	PRMT(MT,3)	21-30
	PRMT(MT,4)	31-40
	PRMT(MT,5)	41-50
	PRMT(MT,6)	51-55

[CARD 3]

MATERIAL MODEL PARAMETERS	PRMT(MT,7)	1-10
	PRMT(MT,8)	11-20
	PRMT(MT,9)	21-30
	PRMT(MT,10)	31-40
	PRMT(MT,11)	41-50
	PRMT(MT,12)	51-55

NOTE: THE ARRAY PRMT(5,12) ON CARDS 2 AND 3 CONTAINS MATERIALS PARAMETERS DEFINED DEPENDING ON THE CONSTITUTIVE MODEL AS FOLLOWS:

1. LINEAR ELASTIC MODEL

PRMT(MT,1) = POISSON'S RATIO
 PRMT(MT,2) = DENSITY
 PRMT(MT,3) = LATERAL PRESSURE COEFFICIENT
 PRMT(MT,4) - PRMT(MT,5) NOT USED
 PRMT(MT,6) = YOUNG'S MODULUS
 PRMT(MT,7) - PRMT(MT,12) NOT USED

2. GRAVEL/STONE HARDENING MODEL FOR BASE

PRMT(MT,1) = POISSON'S RATIO
 PRMT(MT,2) = DENSITY
 PRMT(MT,3) = LATERAL PRESSURE COEFFICIENT
 PRMT(MT,4) = ANGLE OF INTERNAL FRICTION
 PRMT(MT,5) = COHESION
 PRMT(MT,6) = INITIAL GUESS OF RESILIENT MODULUS
 PRMT(MT,7) = K-CONSTANT
 PRMT(MT,8) = N-CONSTANT
 PRMT(MT,9) - PRMT(MT,12) NOT USED

3. BILINEAR SOFTENING MODEL FOR SUBGRADE

PRMT(MT,1) = POISSON'S RATIO
 PRMT(MT,2) = DENSITY
 PRMT(MT,3) = LATERAL PRESSURE COEFFICIENT
 PRMT(MT,4) = ANGLE OF INTERNAL FRICTION
 PRMT(MT,5) = COHESION
 PRMT(MT,6) = INITIAL GUESS OF RESILIENT MODULUS
 PRMT(MT,7) = K1-CONSTANT
 PRMT(MT,8) = K2-CONSTANT
 PRMT(MT,9) = BREAK-POINT MODULUS
 PRMT(MT,10) = BREAK-POINT DEVIATOR STRESS
 PRMT(MT,11) = DEVIATOR STRESS UPPER LIMIT
 PRMT(MT,12) = DEVIATOR STRESS LOWER LIMIT

4. QUADRATIC SOFTENING MODEL FOR SUBGRADE

PRMT(MT,1) = POISSON'S RATIO
 PRMT(MT,2) = DENSITY
 PRMT(MT,3) = LATERAL PRESSURE COEFFICIENT
 PRMT(MT,4) = ANGLE OF INTERNAL FRICTION
 PRMT(MT,5) = COHESION
 PRMT(MT,6) = INITIAL GUESS OF RESILIENT MODULUS
 PRMT(MT,7) = A-CONSTANT
 PRMT(MT,8) = B-CONSTANT
 PRMT(MT,9) = C-CONSTANT
 PRMT(MT,10) = NOT USED
 PRMT(MT,11) = DEVIATOR STRESS UPPER LIMIT
 PRMT(MT,12) = DEVIATOR STRESS LOWER LIMIT

5. LINEAR INTERFACE

NOT AVAILABLE IN THIS VERSION

6. HYPERBOLIC INTERFACE

NOT AVAILABLE IN THIS VERSION

V. NODAL POINT DATA (IN DATAIN)

(I5,3X,2I1,2D10.3,T80,I1) (1 CARD/NODAL POINT)*

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
NODE POINT NUMBER	M	1-5
FIXITY CODE IN X DIRECTION 0 = FREE 1 = FIXED	IA(IIFIX 9	
FIXITY CODE IN Y DIRECTION 0 = FREE 1 = FIXED	IA(IIFIX 10	
X COORDINATE	A(IX	11-20
Y COORDINATE	A(IY	21-30
DATA GENERATION CODE 1 = GENERATED FIXITY CODES SAME AS LAST ONE 0 = GENERATED FIXITY CODES ARE SET TO ZERO (FREE)	NCODE	80

* AUTOMATIC GENERATION OF NODES IS POSSIBLE.
 NODES MUST BE EQUIDISTANT AND ON A STRAIGHT LINE.
 INPUT FIRST AND LAST NODES. FIXITY CODE IS SET TO
 ZERO UNLESS THE LAST NODE CARD DATA GENERATION CODE
 IS SET TO ONE. THEN THE FIXITY CODE IS SET THE SAME
 AS THE LAST NODE.

VI. ELEMENT DATA (IN DATAIN)

(12I5,12X,8I1) (1 CARD/ELEMENT)**

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
ELEMENT NUMBER	M	1-5
NODE I	IA(IIE	6-10
NODE J	IA(IIE	11-15
NODE K	IA(IIE	16-20
NODE L	IA(IIE	21-25
NODE M	IA(IIE	26-30
NODE N	IA(IIE	31-35
NODE O	IA(IIE	36-40
NODE P	IA(IIE	41-45
MATERIAL TYPE NUMBER	IA(IIE	46-50
INTEGRATION TYPE	IA(IIE	51-55
0 = 2X2 POINT		
1 = 3X3 POINT		
FLAG FOR MIDPOINT NODE	ICOR	56-60
GENERATION		
0 = GENERATE		
1 = DONT GENERATE		
ELEMENT GENERATION DATA	I1	73
	I2	74
	I3	75
	I4	76
	I5	77
	I6	78
	I7	79
	I8	80

** AUTOMATIC GENERATION OF ELEMENTS IS POSSIBLE. INPUT THE FIRST ELEMENT OF A PATTERN AND THE FIRST ELEMENT TO BREAK THE PATTERN. IN COLUMNS 73 TO 80 PLACE NUMBERS TO BE ADDED TO PREVIOUS ELEMENT'S NODAL VALUES TO OBTAIN NEXT ELEMENT'S VALUES. PLACE THIS DATA ON THE CARD WHICH BREAKS THE PATTERN, NOT THE FIRST CARD IN THE PATTERN. REFERRING TO FIG.1, TO GENERATE AN ELEMENT BESIDE THE ONE SHOWN, LOOK AT NODE I AND THE CORRESPONDING NODE IN THE NEXT ELEMENT. TAKE THE DIFFERENCE BETWEEN THEIR GLOBAL NODE NUMBERS. PLACE THIS NUMBER IN COLUMN 73 AS THE PATTERN CODE. CONTINUE FOR EACH NODE J,K,L,M,N,O,P AND COLUMNS 74,75,76,77,78,79,80 RESPECTIVELY.

FIG. 1: 2D ISOPARAMETRIC ELEMENT

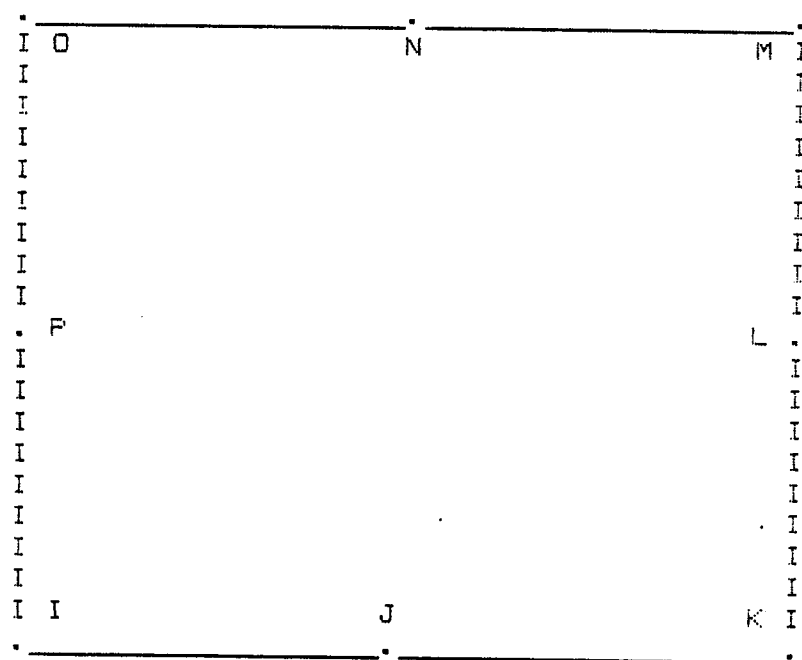
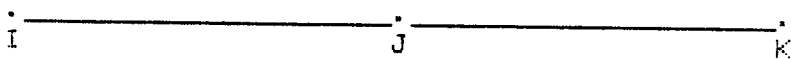


FIG. 2: 2-NODE BAR ELEMENT



FIG. 3: 3-NODE BAR ELEMENT



VII. OUTPUT CONTROL INFORMATION (IN DATAIN)
(A4/16I5) (AS MANY CARDS AS NEEDED)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
FLAG FOR OUTPUT CONTROL	AA	1-4
AA = ALL : OUTPUT PRINTED FOR ALL NODES AND ELEMENTS		
AA = DISP: OUTPUT FOR ALL ELEMENTS BUT LIMITED NODES		
AA = STRS: OUTPUT FOR ALL NODES BUT LIMITED ELEMENTS		
AA = BOTH: OUTPUT FOR LIMITED ELEMENTS AND LIMITED NODES		

1. LIMITED NODES OUTPUT
(NEEDED IF AA EQUALS DISP OR BOTH)

NUMBER OF NODES FOR WHICH OUTPUT IS WANTED	NDSPT	1-5
NODES FOR WHICH OUTPUT IS WANTED	IDSPT(1)	1-5
	IDSPT(2)	6-10
	IDSPT(3)	11-15
	IDSPT(4)	16-20, ETC

2. LIMITED ELEMENTS OUTPUT
(NEEDED IF AA EQUALS STRS OR BOTH)

NUMBER OF ELEMENTS FOR WHICH OUTPUT IS WANTED	NSTPT	1-5
ELEMENTS FOR WHICH OUTPUT IS WANTED	ISTPT(1)	1-5
	ISTPT(2)	6-10
	ISTRPT(3)	11-15
	ISTRPT(4)	16-20, ETC

**** PARTS IX. TO XI. ARE REPEATED
FOR EACH LOAD INCREMENT

IX. INCREMENT CONTROL DATA (IN MASTER)
(7I5, 1X, 5I1) (1 CARD/LOAD INCREMENT)

<DESCRIPTION>	<SYMBOL>	<COLUMNS>
SEQUENCE TYPE	NSEQ	1-5
1 = SURFACE AND/OR POINT LOADS.		
2 = INITIAL BAR STRESSES		
NO. OF SURFACE LOAD CARDS (1 CARD/LOADED ELEMENT)	NSLC	6-10
NO. OF CONCENTRATED LOADS (LOADS AT NODES ONLY)	NFORCE	11-15

MESH MODIFICATION CODE	NMESH	16-20
0 = MESH IS O.K.		
1 = CHANGE MESH (DELETE)		
2 = CHANGE MESH (ADD)		
NO. OF LOAD INCREMENTS FOR THIS SEQUENCE TO BE DIVIDE INTO (DEFAULT = 1)	NSTEPS	21-25
OPTION FOR MOHR-COULOMB FAILURE CRITERION	MOHRC	26-30
1 = YES		
0 = NO		
NUMBER OF NODES WITH SPE- CIFIED NODAL QUANTITIES	NDISP	31-35
FLAG FOR OUTPUT FOR THIS SEQUENCE	IPR(1)	37
0 = OUTPUT		
1 = NO OUTPUT		
FLAG FOR OUTPUT OF ITER- ATIONS	IPR(2)	38
0 = NO OUTPUT		
1 = OUTPUT		
LIMITER FOR SEQUENCE OUTPUT	IPR(3)	39
1 = ALL INCREMENT OUTPUT		
2 = EVERY SECOND INCREMENT		
3 = EVERY THIRD INCREMENT		
4 = ETC		
LAST INCR. ALWAYS OUTPUT		
NOTE: IF IPR(1) = 1 THEN IPR(2) AND IPR(3) ARE NULLIFIED.		
SOLUTION METHOD	IPR(4)	40
0 = FRONTAL		
1 = BANDED		
FLAG FOR CALCULATING STRESSES AT SPECIFIED NODAL POINTS	KSTPLT	41
0 = NO		
1 = YES		

IX.-A. MESH MODIFICATION DATA (IN NODEL)
(NOT NEEDED IF MESH IS NOT TO BE CHANGED)

1. CONTROL INFORMATION
(315) (1 CARD/MESH CHANGE)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
FLAG FOR ELEMENTS ADDED OR DELETED 0 = NO 1 = YES	NIAELM	1-5
FLAG FOR NODES ADDED OR DELETED 0 = NO 1 = YES	NONOD	6-10
FLAG FOR ELEMENTS WHICH HAVE CHANGES IN MATE- RIAL PROPERTIES 0 = NO 1 = YES	NUMELC	11-15

2. ELEMENT DELETION OR ADDITION DATA (IN NODEL)
(I5,1X,A4) (AS MANY CARDS AS NEEDED)***
(NOT NEEDED IF NIAELM = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ELEMENT NUMBER ADDED OR DELETED	NELL	1-5
KEY A BLANK = NO GENERATE GEN = GENERATE LAST = LAST ELEMENT	COD	7-10

3. NODAL DELETION OR ADDITION DATA (IN NODEL)
(I5,3X,2I1,1X,A4) (AS MANY CARDS AS NEEDED)***
(NOT NEEDED IF NONOD = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE NUMBER TO BE ADDED OR DELETED	NODE	1-5
FIXITY CODE FOR X DEGREE OF FREEDOM 0 = ADDED 1 = DELETED	IXX	9
FIXITY CODE FOR Y DEGREE OF FREEDOM 0 = ADDED 1 = DELETED	IYY	10
KEY	COD	12-15

A BLANK = NO GENERATE
 GEN = GENERATE
 LAST = LAST NODE

4. ELEMENT CHANGE DATA (IN NODEL)
 (2I5,1X,A4) (AS MANY CARDS AS NEEDED)***
 (NOT NEEDED IF NUMELC = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ELEMENT NUMBER TO HAVE MATERIAL NUMBER CHANGED	NELL	1-5
NEW MATERIAL NUMBER	MT	6-10
KEY A BLANK = NO GENERATE GEN = GENERATE LAST = LAST ELEMENT	COD	12-15

*** ELEMENTS OR NODES IN NUMERICAL ORDER MAY BE
 GENERATED BY SPECIFYING FIRST ELEMENT OR NODE
 IN A STRING WITH KEY BEING BLANK AND THE LAST
 ELEMENT OR NODE OF STRING WITH KEY BEING GEN
 OR LAST.

X. SEQUENCING DATA FOR INITIAL BAR STRESS SEQUENCE
 (I5 / I5,D10.3)

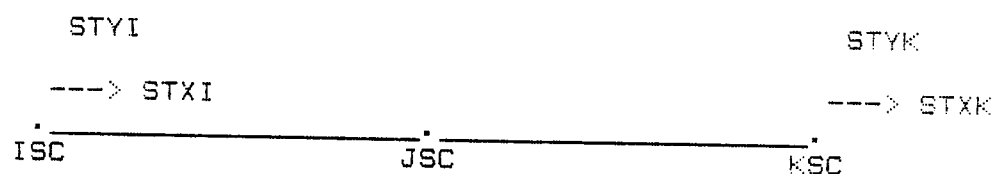
<DESCRIPTION>	<SYMBOL>	<COLUMN>
NO. OF ELEMENTS FOR WHICH STRESS IS SPECIFIED NOTE: THIS CAN BE ADDED.		1-5
ELEMENT NUMBER		1-5
INITIAL STRESS		6-15

X. SURFACE LOAD DATA (IN MASTER)
 (3I5,4D10.3) (1 CARD/SURFACE LOAD)
 (NOT NEEDED IF NO SURFACE LOADS)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
ISC	ISC(I)	1-5
JSC	JSC(I)	6-10
KSC	KSC(I)	11-15

STXI	STXI(I)	16-25
STXK	STXK(I)	26-35
STYI	STYI(I)	36-45
STYK	STYK(I)	46-55

FIG. 4 SURFACE LOADING



XI. CONCENTRATED LOADS DATA (IN MASTER)
(15,2D10.3) (1 CARD/LOAD)
(NOT NEEDED IF NFORCE = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE WHERE LOAD IS APPLIED	NODE	1-5
X FORCE	XFORC	6-15
Y FORCE	YFORC	16-25

XII. SPECIFIED DISPLACEMENTS FOR NODES OTHER
THAN BOUNDARY CONDITION (IN MASTER)
(15,2D10.3) (AS MANY CARDS AS NDISP)
(NOT NEEDED IF NDISP = 0)

<DESCRIPTION>	<SYMBOL>	<COLUMN>
NODE WHERE DISPLACEMENT IS APPLIED	NODE	1-5
X DISPLACEMENT	XDISP	6-15
Y DISPLACEMENT	YDISP	16-25

XIII. NODES AT WHICH STRESSES ARE REQUIRED
(15 / 215) (NOT NEEDED IF KSTPLT=0)

NUMBER OF NODES	NNPST	1-5
-----------------	-------	-----

ELEMENT NUMBER

M

1-5

NODE NUMBER

NODE

6-10

NOTE: NODE IS AN INTEGER 1 THROUGH 8 DETERMINED BY
STARTING AT THE LOWER LEFT CORNER OF THE ELEMENT
(NODE 1) AND NUMBERING IN INCREASING ORDER
COUNTERCLOCKWISE.

APPENDIX E

**LISTING OF THE INPUT FILE SETUP PROGRAM FOR THE PAVEMENT
VERSION OF THE CODE**

INPUT FILE SETUP PROGRAM FOR PCPAVAN

```

C *****
C *      *
C *  PAVINP IS AN INTERACTIVE FORTRAN PROGRAM      *
C *  THAT IS USED TO SETUP AN INPUT FILE FOR      *
C *  THE FLEXIBLE PAVEMENT ANALYSIS CODE PCPAVAN.  *
C *                                              *
C *****
C
C
      CHARACTER*30 FNAME
      COMMON/BLKA1/NEL,NNP,NMAT
      WRITE(6,1005)
      PAUSE 'HIT RETURN TO CONTINUE'
      WRITE(6,1010)
      READ (5,2005) FNAME
      OPEN (UNIT=7,FILE=FNAME,STATUS='NEW',MODE='WRITE')
      CALL SECT1
      CALL SECT2
      CALL SECT3
      CALL SECT4
      CALL SECT5
      CALL SECT6
      CALL SECT7
      CLOSE(UNIT=7)
1005  FORMAT(1H1,////////,5X,'PAVINP.FOR IS AN INTERACTIVE FORTRAN PROGRAM
      1 THAT IS USED TO',/,5X,'SETUP AN INPUT FILE FOR THE PAVEMENT ANALY
      2SIS CODE PAVER...',////////)
1010  FORMAT(///,5X,'ENTER NAME OF INPUT FILE TO BE CREATED: ',,$)
2005  FORMAT(A)
      END
      SUBROUTINE SECT1
C *** SECT1 READS PROBLEM INFOMATION ←
      CHARACTER*1 C
      CHARACTER*78 TITLE
      WRITE(6,1005)
100  WRITE(6,1010)
      READ (5,2005) TITLE
      WRITE(6,1015)
      READ (5,2005) C
      IF (C.NE.'N'.AND.C.NE.'n') GO TO 100
      WRITE(7,2005) TITLE
1005  FORMAT(////2X,32HSECTION ONE: PROBLEM INFORMATION/2X,32H=====
1=====//)
1010  FORMAT(5X,45HENTER PROBLEM TITLE (MAXIMUM 78 CHARACTERS): )
1015  FORMAT(5X,45HARE THERE ANY CORRECTIONS (Y,N,DEFAULT=Y) ? ,,$)
2005  FORMAT(A)
      RETURN

```

```

      END
      SUBROUTINE SECT2
C *** SECT2 READS PROBLEM PARAMETERS
      CHARACTER*1 C
      COMMON/BLKA1/NEL,NNP,NMAT
100  WRITE(6,1005)
      WRITE(6,1006)
      READ *, JOBNO
      WRITE(6,1007)
      READ *, NNP
      WRITE(6,1008)
      READ *, NEL
      WRITE(6,1009)
      READ *, NMAT
      WRITE(6,1010)
      READ *, LCASE
      WRITE(6,1011)
      READ *, NOPT
      WRITE(6,1012)
      READ *, THICK
      WRITE(6,1013)
      READ *, IPRD
      WRITE(6,1014)
      READ *, NITER
      WRITE(6,1015)
      READ *, FTOL
      WRITE(6,1016)
      READ *, DTOL
      WRITE(6,1017)
      READ *, ETOL
      WRITE(6,1018)
      READ (5,2005) C
      IF (C.NE.'N'.AND.C.NE.'n') GO TO 100
      WRITE(7,1020) JOBNO,NNP,NEL,NMAT,LCASE,NOPT,THICK
      WRITE(7,1030) IPRD,NITER,FTOL,DTOL,ETOL
1005  FORMAT(////2X,31HSECTION TWO: PROBLEM PARAMETERS/2X,31H=====
1=====//)
1006  FORMAT(5X,40HENTER JOB NUMBER.....,$)
1007  FORMAT(5X,40HENTER NUMBER OF NODES.....,$)
1008  FORMAT(5X,40HENTER NUMBER OF ELEMENTS.....,$)
1009  FORMAT(5X,40HENTER NUMBER OF MATERIAL TYPES.....,$)
1010  FORMAT(5X,40HENTER NUMBER OF LOAD CASES.....,$)
1011  FORMAT(//,5X,'PROBLEM TYPES AVAILABLE:' /7X,'AXISYMMETRIC ----> USE
1 0' /7X,'PLANE STRAIN ----> USE 1' /7X,'PLANE STRESS ----> USE 2' /5X
2,40HENTER OPTION.....,$)
1012  FORMAT(5X,40HENTER THICKNESS OF ELEMENTS.....,$)
1013  FORMAT(//,5X,'SOLUTION ALGORITHMS AVAILABLE:' /7X,'INCREMENTAL INIT
1IAL STIFFNESS -----> USE 1' /7X,'INCREMENTAL TAN
2GENTIAL STIFFNESS -----> USE 2' /7X,'INCREMENTAL CO
3MBINED INITIAL-TANGENTIAL STIFFNESS ----> USE 3' /7X,'INCREMENTAL D
4IRECT ITERATIVE -----> USE 4' /5X,40HENTER OPTI
5ON.....,$)
1014  FORMAT(5X,40HENTER THE MAXIMUM NUMBER OF ITERATIONS...,$)
1015  FORMAT(5X,40HENTER TOLERANCE ON RESIDUAL FORCES.....,$)
1016  FORMAT(5X,40HENTER TOLERANCE ON DISPLACEMENTS.....,$)

```

```

1017 FORMAT(5X,40HENTER TOLERANCE ON RESILIENT MODULI.....,$)
1018 FORMAT(5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? ,,$)
1020 FORMAT(6I5,D10.3)
1030 FORMAT(2I5,3D10.3)
2005 FORMAT(A)
      RETURN
      END
      SUBROUTINE SECT3
C *** SECT3 READS GRAPHICS INFORMATION
      CHARACTER*1 C
      WRITE(6,1005)
100  WRITE(6,1010)
      READ *, IWRIT
      WRITE(6,1015)
      READ *, IMESH
      WRITE(6,1020)
      READ *, JMESH
      WRITE(6,1025)
      READ *, KMESH
      WRITE(6,1030)
      READ *, IVECT
      WRITE(6,1020)
      READ *, JVECT
      WRITE(6,1035)
      READ *, KVECT
      WRITE(6,1040)
      READ *, ISTRS
      WRITE(6,1020)
      READ *, JSTRS
      WRITE(6,1035)
      READ *, KSTRS
      WRITE(6,1045)
      READ *, IDMES
      WRITE(6,1020)
      READ *, JDMES
      WRITE(6,1035)
      READ *, KDMES
      WRITE(6,1036)
      READ *, DMAGN
      WRITE(6,1050)
      READ *, IZOOM
      WRITE(6,1020)
      READ *, JZOOM
      WRITE(6,1055)
      READ (5,2005) C
      IF (C.NE.'N'.AND.C.NE.'n') GO TO 100
      WRITE(7,1060) IWRIT,IMESH,JMESH,KMESH,IVECT,JVECT,KVECT,ISTRS,JSTR
1S,KSTRS,IDMES,JDMES,KDMES,IZOOM,JZOOM,DMAGN
      IF (IZOOM.EQ.1) THEN
200  WRITE(6,1051)
      READ *, XZ1
      WRITE(6,1052)
      READ *, YZ1
      WRITE(6,1053)
      READ *, WZ

```

```

WRITE(6,1054)
READ *, HZ
WRITE(6,1055)
READ (5,2005) C
IF (C.NE.'N'.AND.C.NE.'n') GO TO 200
WRITE(7,1070) XZ1,YZ1,WZ,HZ
ENDIF
1005 FORMAT(///2X,35HSECTION THREE: GRAPHICS INFORMATION/2X,35H=====
1=====//)
1010 FORMAT(5X,44HOPTION FOR WRITING SELECTED RESULTS TO DISK:/7X,25HWR
1ITE ----- 1/7X,25HDONT WRITE ----- 0/5X,26HENTE
2R OPTION.....,$)
1015 FORMAT(/5X,33HOPTION FOR DRAWING ORIGINAL MESH:/7X,25HDRAW -----
1----- 1/7X,25HDONT DRAW ----- 0/5X,26HENTER OPTION..
2.....,$)
1020 FORMAT(/5X,23HOPTION FOR SCREEN DUMP:/7X,25HDUMP -----
1- 1/7X,25HDONT DUMP ----- 0/5X,26HENTER OPTION.....
2...,$)
1025 FORMAT(/5X,26HLIMITER ON LOAD SEQUENCES:/7X,25HALL LOAD SEQUENCES
1---- 1/7X,30HEVERY OTHER SEQUENCE -- 2, ETC/7X,30HLAST SEQUENCE AL
2WAYS INCLUDED /5X,26HENTER OPTION.....,$)
1030 FORMAT(/5X,36HOPTION TO PLOT DISPLACEMENT VECTORS:/7X,25HPLOT ----
1----- 1/7X,25HDONT PLOT ----- 0/5X,26HENTER OPTIO
2N.....,$)
1035 FORMAT(/5X,22HLIMITER ON LOAD STEPS:/7X,25HALL LOAD STEPS -----
1 1/7X,30HEVERY OTHER LOAD STEP - 2, ETC/7X,30HLAST LOAD STEP ALWAY
2S INCLUDED/5X,26HENTER OPTION.....,$)
1036 FORMAT(/5X,40HENTER MAGNIFICATION OF DISPLACEMENTS.....,$)
1040 FORMAT(/5X,33HOPTION FOR DRAWING STRESS STATES:/7X,25HDRAW -----
1----- 1/7X,25HDONT DRAW ----- 0/5X,26HENTER OPTION..
2.....,$)
1045 FORMAT(/5X,33HOPTION FOR DRAWING DEFORMED MESH:/7X,25HDRAW -----
1----- 1/7X,25HDONT DRAW ----- 0/5X,26HENTER OPTION..
2.....,$)
1050 FORMAT(/5X,37HOPTION TO ZOOM ON A PART OF THE MESH:/7X,25HZOOM ---
1----- 1/7X,25HDONT ZOOM ----- 0/5X,26HENTER OPTI
2ON.....,$)
1051 FORMAT(/5X,50HENTER X-COORD. OF LOWER-LEFT CORNER OF ZOOM RECT..,$
1)
1052 FORMAT(5X,50HENTER Y-COORD. OF LOWER-LEFT CORNER OF ZOOM RECT..,$)
1053 FORMAT(5X,50HENTER WIDTH OF ZOOM RECTANGLE.....,$)
1054 FORMAT(5X,50HENTER HEIGHT OF ZOOM RECTANGLE.....,$)
1055 FORMAT(//,5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? ,,$)
1060 FORMAT(15,4(1X,I1,I1,I2),1X,I1,2X,I1,D10.3)
1070 FORMAT(4D10.3)
2005 FORMAT(A)
RETURN
END
SUBROUTINE SECT4
C *** SECT4 READS MATERIAL PROPERTIES
CHARACTER*1 C
COMMON/BLKA1/NEL,NNP,NMAT
DIMENSION JCODE(5),IELTYP(5),PRMT(5,12)
WRITE(6,1005)
DO 200 I=1,NMAT

```

```

100  WRITE(6,1010) I
      READ *, JCODE(I)
      WRITE(6,1015) I
      READ *, IELTYP(I)
      WRITE(6,1100)
      READ (5,2005) C
      IF (C.NE.'N'.AND.C.NE.'n') GO TO 100
105  WRITE(6,1110)
      READ *, PRMT(I,1)
      WRITE(6,1120)
      READ *, PRMT(I,2)
      JCOD=JCODE(I)+1
      GO TO (110,120,120,120,180,180) ,JCOD
110  WRITE(6,1160)
      READ *, PRMT(I,6)
      GO TO 180
120  WRITE(6,1130)
      READ *, PRMT(I,3)
      WRITE(6,1140)
      READ *, PRMT(I,4)
      WRITE(6,1150)
      READ *, PRMT(I,5)
      WRITE(6,1165)
      READ *, PRMT(I,6)
130  GO TO (180,140,150,160,180,180) ,JCOD
140  WRITE(6,1170)
      READ *, PRMT(I,7)
      WRITE(6,1180)
      READ *, PRMT(I,8)
      GO TO 180
150  WRITE(6,1172)
      READ *, PRMT(I,7)
      WRITE(6,1182)
      READ *, PRMT(I,8)
      WRITE(6,1190)
      READ *, PRMT(I,9)
      WRITE(6,1200)
      READ *, PRMT(I,10)
      WRITE(6,1210)
      READ *, PRMT(I,11)
      WRITE(6,1220)
      READ *, PRMT(I,12)
      GO TO 180
160  WRITE(6,1174)
      READ *, PRMT(I,7)
      WRITE(6,1184)
      READ *, PRMT(I,8)
      WRITE(6,1192)
      READ *, PRMT(I,9)
      WRITE(6,1210)
      READ *, PRMT(I,11)
      WRITE(6,1220)
      READ *, PRMT(I,12)
180  WRITE(6,1100)
      READ (5,2005) C

```

```

      IF (C.NE.'N'.AND.C.NE.'n') GO TO 105
      WRITE(7,1300) JCODE(I),IELTYP(I)
      WRITE(7,1310) (PRMT(I,J), J=1,6)
      WRITE(7,1310) (PRMT(I,J), J=7,12)
200   CONTINUE
1005  FORMAT(////2X,33HSECTION FOUR: MATERIAL PROPERTIES/2X,33H=====
1=====//)
1010  FORMAT(/5X,30HCONSTITUTIVE MODELS AVAILABLE:/7X,38HLINEAR ELASTIC
1MODEL -----> USE 0/7X,38HGRAVEL/STONE BASE MODEL -----> USE
2 1/7X,38HBILINEAR SUBGRADE MODEL -----> USE 2/7X,38HQUADRATIC SU
3BGRADE MODEL -----> USE 3/7X,38HLINEAR INTERFACE MODEL ----->
4USE 4/7X,38HHYPERBOLIC INTERFACE MODEL ----> USE 5/5X,33HENTER OPT
5ION FOR MATERIAL NUMBER ,I1,15H....., $)
1015  FORMAT(5X,24HELEMENT TYPES AVAILABLE:/7X,54HEIGHT-NODE QUADRILATER
1AL SOIL ELEMENT -----> USE 1/7X,54HEIGHT-NODE QUADRILATERAL ST
2RUCTURE ELEMENT ----> USE 2/7X,54HINTERFACE ELEMENT -----
3-----> USE 3/7X,54HTHREE-NODE BAR ELEMENT -----
4-----> USE 4/7X,54HTWO-NODE BAR ELEMENT -----
5-----> USE 5/5X,33HENTER OPTION FOR MATERIAL NUMBER ,I1,15H.....
6....., $)
1100  FORMAT(5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? , $)
1110  FORMAT(5X,45HENTER POISSON'S RATIO....., $)
1120  FORMAT(5X,45HENTER DENSITY....., $)
1130  FORMAT(5X,45HENTER LATERAL PRESSURE COEFFICIENT....., $)
1140  FORMAT(5X,45HENTER ANGLE OF INTERNAL FRICTION....., $)
1150  FORMAT(5X,45HENTER COHESION....., $)
1160  FORMAT(5X,45HENTER YOUNG'S MODULUS....., $)
1165  FORMAT(5X,45HENTER INITIAL GUESS OF RESILIENT MODULUS....., $)
1170  FORMAT(5X,45HENTER K-CONSTANT....., $)
1172  FORMAT(5X,45HENTER K1-CONSTANT....., $)
1174  FORMAT(5X,45HENTER A-CONSTANT....., $)
1180  FORMAT(5X,45HENTER N-CONSTANT....., $)
1182  FORMAT(5X,45HENTER K2-CONSTANT....., $)
1184  FORMAT(5X,45HENTER B-CONSTANT....., $)
1190  FORMAT(5X,45HENTER BREAK-POINT RESILIENT MODULUS ERI....., $)
1192  FORMAT(5X,45HENTER C-CONSTANT....., $)
1200  FORMAT(5X,45HENTER BREAK-POINT DEVIATOR STRESS SDI....., $)
1210  FORMAT(5X,45HENTER UPPER-LIMIT ON DEVIATOR STRESS....., $)
1220  FORMAT(5X,45HENTER LOWER-LIMIT ON DEVIATOR STRESS....., $)
1300  FORMAT(2I5)
1310  FORMAT(6D10.3)
2005  FORMAT(A)
      RETURN
      END
      SUBROUTINE SECT5
C *** SECT5 READS NODAL POINT DATA
      CHARACTER*1 C
      COMMON/BLKA1/NEL,NNP,NMAT
      DIMENSION N(10),IFX(10),IFY(10),X(10),Y(10),NCODE(10)
      WRITE(6,1005)
      WRITE(6,1010)
100   WRITE(6,1015)
      NC=0
110   NC=NC+1
      READ *, N(NC),IFX(NC),IFY(NC),X(NC),Y(NC),NCODE(NC)

```

```

115  IF (NC.EQ.10.OR.N(NC).EQ.NNP) THEN
      WRITE(6,1020)
      READ (5,2005) C
      IF (C.NE.'N'.AND.C.NE.'n') GO TO 100
      WRITE(7,1025) (N(I),IFX(I),IFY(I),X(I),Y(I),NCODE(I), I=1,NC)
      IF (N(NC).EQ.NNP) GO TO 120
      GO TO 100
    ENDIF
      GO TO 110
120  CONTINUE
1005  FORMAT(////,2X,30HSECTION FIVE: NODAL POINT DATA/2X,30H=====
1=====//5X,55H*** AUTOMATIC GENERATION OF NODES IS P
2OSSIBLE IF NODES/9X,51HARE EQUIDISTANT AND ON A STRAIGHT LINE. INP
3UT FIRST/9X,51HAND LAST NODES. FIXITY CODES FOR THE AUTOMATICALLY
4/9X,51HGENERATED NODES ARE SET TO ZERO; HOWEVER, IF NCODE/9X,51HI
5S ENTERED AS ONE, THEN THE FIXITY CODES ARE SET TO/9X,23HTHOSE OF
6THE LAST NODE./5X,55H*** MISTAKES CAN BE CORRECTED AFTER EVERY TEN
7 ENTERIES.)
1010  FORMAT(5X,55H*** NODE DATA IS ENTERED AS FOLLOWS: N,FX,FY,X,Y,NCOD
1E./9X,6HWHERE:/10X,19HN      = NODE NUMBER/10X,51HFX      = FIXITY CO
2DE IN X-DIRECTION (0=FREE,1=FIXED)/10X,51HFY      = FIXITY CODE IN Y
3-DIRECTION (0=FREE,1=FIXED)/10X,20HX      = X-COORDINATE/10X,20HY
4      = Y-COORDINATE/10X,39HNCODE = CODE FOR FIXITY-CODE GENERATION/1
59X,42HO = GENERATED FIXITY CODES ARE SET TO ZERO/19X,50H1 = GENERA
6TED FIXITY CODES ARE SAME AS LAST NODE'S)
1015  FORMAT(/,5X,25HENTER: N,FX,FY,X,Y,NCODE./)
1020  FORMAT(5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? , $)
1025  FORMAT(15,3X,2I1,2D10.3,49X,I1)
2005  FORMAT(A)
      RETURN
    END
  SUBROUTINE SECT6
C *** SECT6 READS ELEMENT DATA
  CHARACTER*1 COR
  INTEGER C,E,O,P,Q
  COMMON/BLKA1/NEL,NNP,NMAT
  DIMENSION E(5),I(5),J(5),K(5),L(5),M(5),N(5),O(5),P(5),MT(5),INT(5
1),MD(5),I1(5),I2(5),I3(5),I4(5),I5(5),I6(5),I7(5),I8(5)
  WRITE(6,1005)
  WRITE(6,1010)
  WRITE(6,1015)
100  WRITE(6,1020)
      C=1
      READ *, E(1)
      READ *, I(1),J(1),K(1),L(1),M(1),N(1),O(1),P(1),MT(1),INT(1),MD(1)
110  C=C+1
      READ *, E(C)
      IF (E(C).EQ.E(C-1)) THEN
        READ *, I(C),J(C),K(C),L(C),M(C),N(C),O(C),P(C),MT(C),INT(C),MD(C)
      ELSE
        READ *, I(C),J(C),K(C),L(C),M(C),N(C),O(C),P(C),MT(C),INT(C),MD(C)
1, I1(C),I2(C),I3(C),I4(C),I5(C),I6(C),I7(C),I8(C)
      ENDIF
      IF (C.EQ.5.OR.E(C).EQ.NEL) THEN
        WRITE(6,1025)

```

```

      READ (5,2005) COR
      IF (COR.NE.'N'.AND.COR.NE.'n') GO TO 100
      WRITE(7,1030) (E(Q),I(Q),J(Q),K(Q),L(Q),M(Q),N(Q),O(Q),P(Q),MT(Q),
1INT(Q),MD(Q),I1(Q),I2(Q),I3(Q),I4(Q),I5(Q),I6(Q),I7(Q),I8(Q), Q=1,
2C)
      IF (E(C).EQ.NEL) GO TO 120
      ELSE
      GO TO 110
      ENDIF
      GO TO 100
120  CONTINUE
1005  FORMAT(///2X,25HSECTION SIX: ELEMENT DATA/2X,25H=====
1=====/)
1010  FORMAT(5X,70H*** AUTOMATIC GENERATION OF ELEMENTS IS POSSIBLE. INP
1UT THE INCIDENCES/9X,66HOF THE FIRST ELEMENT IN A PATTERN, THEN WI
2TH THE INCIDENCES OF THE/9X,66HFIRST ELEMENT TO BREAK THE PATTERN
3, INPUT THE ELEMENT GENERATION/9X,66HDATA WHICH CONSIST OF THE EI
4GHT NUMBERS THAT ARE ADDED TO PREVIOUS/9X,61HELEMENT'S NODAL VALUE
5S TO OBTAIN NEXT ELEMENT'S NODAL VALUES.)
1015  FORMAT(5X,39H*** ELEMENT DATA IS ENTERED AS FOLLOWS:/6X,74HNE, RET
1URN. I,J,K,L,M,N,O,P,MAT,INT,MID, (OPTIONAL: I1,I2,I3,I4,I5,I6,I7,I8
2)/6X,66HWHERE:/7X,25HEN      = ELEMENT NUMBER/7X,29HI TO P      = ELE
3MENT INCIDENCES/7X,31HMAT      = MATERIAL TYPE NUMBER/7X,57HINT
4      = INTEGRATION TYPE NUMBER (0 = 2 X 2, 1 = 3 X 3)/7X,57HMID
5      = FLAG FOR MIDPOINT NODE GENERATION (0=YES,1=NO)/7X,45HI1 TO I8 =
6 ELEMENT GENERATION DATA (OPTIONAL)/5X,54H*** MISTAKES CAN BE CORR
7ECTED AFTER EVERY FIVE ENTRIES)
1020  FORMAT(/9X,71HENTER: EN,RETURN. I,J,K,L,M,N,O,P,MAT,INT,MID, (I1,I2
1,I3,I4,I5,I6,I7,I8))
1025  FORMAT(5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? ,#)
1030  FORMAT(12I5,12X,8I1)
2005  FORMAT(A)
      RETURN
      END
      SUBROUTINE SECT7
C *** SECT7 READS OUTPUT CONTROL INFORMATION
      CHARACTER COR*1,ALL*3,DISP*4,STRS*4,BOTH*4
      COMMON/BLKA1/NEL,NNP,NMAT
      DIMENSION N(100)
      WRITE(6,1005)
      WRITE(6,1010)
      READ *, NO
      WRITE(6,1015)
      READ *, MO
C *** ALL
      IF (NO.EQ.NNP.AND.MO.EQ.NEL) THEN
          WRITE(6,1030)
          WRITE(7,1200) ALL
          GO TO 150
      ENDIF
C *** DISP
      IF (NO.LT.NNP.AND.MO.EQ.NEL) THEN
          WRITE(6,1025)
100  WRITE(6,1040)
110  READ*, (N(I), I=1,NO)

```

```

        WRITE(6,1050)
        READ(5,1200) COR
        IF(COR.NE.'N'.AND.COR.NE.'n') GO TO 110
        WRITE(7,1200) DISP
        WRITE(7,1210) (N(I), I=1,NO)
    ENDIF
C *** STRS
    IF(NO.EQ.NNP.AND.MO.LT.NEL) THEN
        WRITE(6,1035)
120    WRITE(6,1045)
130    READ *, (N(I), I=1,MO)
        WRITE(6,1050)
        READ(5,1200) COR
        IF(COR.NE.'N'.AND.COR.NE.'n') GO TO 130
        WRITE(7,1200) STRS
        WRITE(7,1210) (N(I), I=1,MO)
    ENDIF
C *** BOTH
    IF(NO.LT.NNP.AND.MO.LT.NEL) THEN
        WRITE(6,1020)
        GO TO 100
        GO TO 120
    ENDIF
150    CONTINUE
1005    FORMAT(///2X,41HSECTION SEVEN: OUTPUT CONTROL INFORMATION/2X,41H=
1=====//)
1010    FORMAT(5X,55HENTER NUMBER OF NODES FOR WHICH OUTPUT IS WANTED.....
1..,$)
1015    FORMAT(5X,55HENTER NUMBER OF ELEMENTS FOR WHICH OUTPUT IS WANTED..
1..,$)
1020    FORMAT(/5X,65H*** OUTPUT FOR LIMITED NODES AND LIMITED AND LIMITE
1D ELEMENTS ***/)
1025    FORMAT(/5X,65H***** OUTPUT FOR LIMITED NODES BUT ALL ELEMEN
1TS *****/)
1030    FORMAT(/5X,65H***** OUTPUT FOR ALL NODES AND ALL ELEMENTS *
1*****/)
1035    FORMAT(/5X,65H***** OUTPUT FOR ALL NODES BUT LIMITED ELEMENTS
1 *****/)
1040    FORMAT(5X,40HENTER NODES FOR WHICH OUTPUT IS DESIRED:)
1045    FORMAT(5X,43HENTER ELEMENTS FOR WHICH OUTPUT IS DESIRED:)
1050    FORMAT(5X,40HARE THERE ANY CORRECTIONS (Y,N,DEF=Y) ? , $)
1200    FORMAT(A)
1210    FORMAT(16I5)
        RETURN
    END

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VITA

Jomaa Ben-Hassine was born in the town of La Chebba located at the center of the Mediterranean coastline of Tunisia on May 24th, 1963. He attended the Ecole Primaire de Ghedabna, Lycee Mixte de Ksour-Essaf, then Lycee Mixte de La Chebba where he obtained his Baccalaureate Degree. As part of his college education, he attended Ohio Wesleyan University, Delaware for one year and then transferred to the University of Tennessee, Knoxville where he received his Bachelor of Science Degree in Civil Engineering with Honors in March of 1985. During the fall of 1987, he completed all the requirements for a Master of Engineering Degree in Civil Engineering with Geotechnical Engineering as a major area of interest. Currently, he is enrolled at the University of Tennessee for a Doctorate of Philosophy Degree in the same major. Jomaa Ben-Hassine is a member of such honor societies as Tau Beta Pi, Chi Epsilon and Gamma Beta Phi and of such professional societies as American Concrete Institute (ACI.)