PAVEMENT EVALUATION AND OVERLAY DESIGN USING VIBRATORY NONDESTRUCTIVE TESTING (NDT)
PAVEMENT EVALUATION AND OVERLAY DESIGN USING VIBRATORY NONDESTRUCTIVE TESTING AND LAYERED ELASTIC THEORY

Volume I
Development of Procedure

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Geotechnical Laboratory
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FINAL REPORT

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The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.
A procedure is developed for determining the allowable load-carrying capacities and the required overlay thicknesses of airport pavements. A layered elastic theory approach is used with vibratory nondestructive tests supplying the dynamic responses of pavements. For a given pavement, a computer program SUBE is used to determine the value of the subgrade Young's modulus from the measured dynamic responses, and a computer program PAVEVAL, which is based on the layered elastic theory, is used to calculate the allowable load-carrying capacity and the required overlay thickness. Limiting subgrade strains and horizontal stresses in pavement layers are used as criteria for determining load-carrying capacities and overlay thickness requirements. Single- and multiple-wheel loadings are considered. Volume II of this report presents a validation of these procedures for three airport sites.
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### Notes

1. *F* = 9/5(°C) + 32. For other exact conversions and more detailed tables, see NSR WDC publ. 285, Units of Weight and Measure, Price 12.25, BD Catalog No. C13/10-285.
This study was conducted during the period October 1977 to December 1978 by personnel of the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), for the U. S. Department of Transportation, Federal Aviation Administration, as a part of Inter-Agency Agreement No. DOT FA73WAI-377, "New Pavement Design Methodology."

The study was conducted under the general supervision of Messrs. J. P. Sale and R. G. Ahlvin, Chief and Assistant Chief, respectively, of GL; R. L. Hutchinson and H. H. Ulery, Jr., Chief and Principal Technical Advisor, respectively, of the Pavement Systems Division; and under the direct supervision of A. H. Joseph, Chief of the Engineering Investigation Testing and Validation Group; and J. W. Hall, Jr., Chief of the Prototype Testing and Evaluation Unit. The programming for this study was accomplished in part by Mr. Ricky Austin, Research and Analysis Group. Significant contributions were made by Messrs. J. L. Green and A. J. Bush III of the Prototype Testing and Evaluation Unit, and by Dr. W. R. Barker of the Research and Analysis Group. The report was written by Dr. R. A. Weiss.

COL John L. Cannon, CE, and COL Nelson P. Conover, CE, were Directors of the WES during the conduct of this study and the preparation of this report. The Technical Director was Mr. F. R. Brown.
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INTRODUCTION

BACKGROUND

The increasing expense of pavement construction and rehabilitation makes it essential to have a fast and reliable method of accurately predicting the allowable load-carrying capacity and the required overlay thickness for pavement upgrading. Vibratory nondestructive testing can play an important part for the rapid evaluation of airport pavements.¹⁻⁶ The U. S. Army Engineer Waterways Experiment Station (WES) was requested to develop a pavement evaluation method based on vibratory nondestructive testing combined with layered elastic theory. This study combines the layered elastic theory for calculating stress and strain in a pavement with the nonlinear theory of dynamic pavement response that describes the vibratory nondestructive test data to produce a working method, including computer programs, for evaluating pavements and designing overlays.

The combined method of layered elasticity theory and vibratory nondestructive testing is compared with the conventional method that uses the California Bearing Ratio (CBR) for evaluating asphaltic concrete (AC) pavements and with the Westergaard method for evaluating portland cement concrete (PCC) pavements.⁷ It is also compared with the pavement evaluation method that uses a correlation between the strength of a pavement and the dynamic stiffness modulus (DSM) that is obtained from vibratory nondestructive testing.¹

The CBR and Westergaard methods require destructive tests to measure the CBR and the coefficient of subgrade reaction, respectively. To circumvent the destructive tests, a vibratory nondestructive test method, which directly correlates the allowable load-carrying capacity and the required overlay thickness to a mechanical impedance that is measured at the pavement surface (the DSM), was developed at the WES for evaluating AC and PCC pavements.

The DSM is obtained from vibratory nondestructive test data that are obtained with the WES electrohydraulic vibrator, which can
generate dynamic loads up to 15 kips with a constant 16-kip static load (WES 16-kip vibrator) and a constant frequency of 15 Hz. These data consist of dynamic load-deflection curves that are measured at the pavement surface. The dynamic load-deflection curves are nonlinear in general, and the DSM is the slope of the dynamic load-deflection curve for a dynamic load of about 10-14 kips. The measured DSM is corrected to a common pavement temperature of 70°F, and the corrected value of the DSM is correlated to the allowable load-carrying capacity and the required overlay thickness of a pavement. The DSM method is empirical and does not take into consideration the layered elastic structure of the pavement or the interface conditions between the pavement layers.

In order to improve on the method of directly correlating pavement performance with vibratory nondestructive test data, an attempt was made to combine the layered elastic theory of pavements with the pavement impedance values measured by vibratory nondestructive tests. In this way, the pavement structure could be considered. The layered elastic model of pavements required the Young's modulus and the Poisson's ratio of the subgrade and pavement layers to be known. The elastic moduli of the pavement layers are estimated by various means, and only the subgrade Young's modulus is obtained by vibratory nondestructive tests.

The pavement evaluation method presented herein consists of determining the subgrade Young's modulus from the dynamic response of a pavement measured by vibratory nondestructive tests and using the determined value of the subgrade Young's modulus in the layered elastic theory to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement. Two computer programs, SUBE and PAVEVAL, are used for the necessary computations and to obtain the results.

The subgrade Young's modulus is determined from dynamic load-deflection curves that are measured at the pavement surface. In general, these dynamic load-deflection curves are nonlinear, and a nonlinear dynamic theory is required to extract the value of the subgrade Young's modulus from these measured curves. The nonlinear
Dynamic theory is used to remove the extraneous effects of the static and dynamic loads developed by the vibrator on the predicted values of the subgrade Young's modulus. The value of the subgrade Young's modulus used for calculating the allowable load-carrying capacity and the required overlay thickness of a pavement should reflect only the stress conditions in the subgrade due to the aircraft loading and the natural overburden pressure. The computer program SUBE was developed from the nonlinear theory of pavement response to dynamic loads and is used to determine the subgrade Young's modulus from the measured dynamic load-deflection curves.

Within the context of the layered elastic theory, pavements are represented by a stack of elastic layers, the subgrade being of infinite extent. This layered elastic theoretical model of a pavement structure is used to calculate the elastic stress and strain at any point in the pavement or the subgrade. Each pavement layer is characterized by a Poisson's ratio (ν), a Young's modulus (E), and a layer thickness (h). The Shell BISAR computer program is based on the layered elastic theory and relates the stress and the strain in each pavement layer to the static load applied to the surface of a pavement. The computer program PAVEVAL that is used for pavement evaluation and overlay design is a modification of the BISAR program. Figure 1 represents a typical pavement structure subjected to a loading according to the layered elastic theory approach.

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Figure 1. Typical pavement structure with loading according to the layered elastic theory.
The computer programs SUBE and PAVEVAL were developed on the IBM 360/65 computer and are designed for practical use by pavement engineers.

OBJECTIVES

A pavement evaluation procedure is required that will use vibratory nondestructive testing and analysis of data to obtain the value of the subgrade modulus for input into the layered elastic theory for calculating stresses and strains in a pavement. The basic objectives of this study are:

a. To further develop and evaluate a theoretical procedure for determining the subgrade Young's modulus from vibratory nondestructive test data.

b. To determine the allowable load-carrying capacity for AC and PCC pavements for single- and multiple-wheel loadings using the subgrade modulus in the layered elastic theory.

c. To determine the overlay thickness required to upgrade AC and PCC pavements for single- and multiple-wheel loadings using elastic pavement parameters calculated from vibratory nondestructive testing results in the layered elastic theory.

SCOPE

To achieve these objectives, theoretical and experimental work was done.

THEORETICAL STUDIES

The theoretical studies included:

a. A logical method of selecting the values of the elastic moduli of each pavement layer.

b. The development of the nonlinear dynamic computer program SUBE to predict the values of the subgrade Young's modulus from measured vibratory nondestructive test data.

c. The determination of the limiting vertical strain in the subgrade and the limiting tensile strain in the AC layer of AC pavements, and a limiting tensile stress criterion in PCC pavements as design criteria to be used with the layered elastic pavement model.

d. The development of the PAVEVAL layered elastic computer program to calculate the allowable load-carrying capacity and the required overlay thickness for AC and PCC pavements.
with single- and multiple-wheel loadings. A comparison with conventional CBR and Westergaard methods is made.

EXPERIMENTAL STUDIES

Dynamic load-deflection curves and CBR values were measured in the field for PCC and AC pavements.
MATERIAL PARAMETERS AND FAILURE CRITERIA REQUIRED FOR PAVEMENT EVALUATION AND OVERLAY DESIGN

GENERAL CONSIDERATIONS

Repeated aircraft loadings on a pavement will eventually lead to a failure of the pavement. The ultimate purpose of the nondestructive testing of a pavement is to estimate the allowable load-carrying capacity of a pavement for a specified number of yearly load repetitions or to determine the overlay thickness required to upgrade a pavement when the operating aircraft weight and yearly number of load repetitions are specified.\(^1\) The estimation of the allowable load-carrying capacity and the required overlay thickness requires a knowledge of the failure processes that occur in AC and PCC pavements. Vibratory nondestructive testing should supply some of the pavement parameters that enter into the physical description of the failure processes.\(^2\)\(^-\)\(^4\)

Pavements fail for a variety of reasons. Many pavements fail because the pavement does not properly protect the subgrade from large stresses and strains that can cause excessive plastic and elastic deformation of the soil in the subgrade. Experience has shown that the condition of failure in AC pavements may be described by a limiting elastic (resilient) vertical strain in the top of the subgrade and a limiting tensile strain at the bottom of the AC pavement layer, while the condition of failure in PCC pavements can be described by a limiting tensile stress at the bottom of the PCC layer.\(^8\)\(^,\)\(^9\) These limiting values of stress and strain are related to the allowable load-carrying capacity and the required overlay thickness of a pavement through the structure of the pavement, i.e., through the thickness and the material type of each layer of the pavement and the subgrade.

The materials in the pavement layers must be described by material parameters, which determine the stress-strain characteristics. The proper mechanical parameters chosen to describe the pavement material will depend on the type of problem under consideration. For instance, if the time history of the plastic flow of the pavement
material is of interest, then some plastic flow parameters relating permanent strain to the operating stress must be introduced. If the resilient properties or the incipient plastic flow characteristics of pavement materials are of interest, the Young's modulus and the Poisson's ratio of the subgrade and pavement layers are sufficient for a complete description.

FAILURE IN AC PAVEMENTS

The failure of AC pavements generally occurs by two processes: (a) cracking of the bituminous wearing surface and (b) rutting of the wearing surface along the wheel paths. The fatigue cracking along the wearing surface due to repeated flexural loadings is determined by the magnitude of the tensile strain at the bottom of the wearing surface, while the rutting of the wearing surface may be governed in part by the vertical compressive strain at the top of the subgrade and by the flow of the AC material. Therefore, in this study, the allowable load-carrying capacity and the required overlay thickness for AC pavements will be determined mainly by a limiting vertical compressive strain at the top of the subgrade. However, this may lead to erroneous values because of the gross oversimplifications involved.

For a given load at the pavement surface, the values of the stress and the strain in the pavement and the subgrade depend on the Young's modulus and the Poisson's ratio of the subgrade and each pavement layer. Therefore, if the elastic moduli of the pavement layers are known, it is the Young's modulus of the subgrade that is the unknown parameter determining stress and strain in the pavement and the subgrade. This parameter must be obtained by vibratory nondestructive testing.

FAILURE IN PCC PAVEMENTS

It is assumed herein that PCC pavements fail because of fatigue cracking associated with the repeated flexural stress in the PCC layer. Actually, many failures occur at joints, but this condition is not considered in this study. The fatigue cracking of the wearing surface of PCC pavements is governed by the tensile stress at the bottom of the
wearing surface, and the value of this stress, for a given operating load at the pavement surface, is determined by the elastic moduli of the subgrade and pavement layers. Assuming that the elastic moduli of the pavement layers are known, it is the subgrade Young's modulus that is the unknown parameter determining the operating value of the tensile stress at the bottom of the PCC layer. This elastic parameter must be supplied by vibratory nondestructive testing.

PAVEMENT EVALUATION AND OVERLAY DESIGN

The computer program PAVEVAL was written to incorporate the material parameters and the limiting stress and strain criteria into a procedure for calculating the allowable load-carrying capacity and the overlay thickness required for pavement upgrading. PAVEVAL, used in conjunction with the computer program SUBE that predicts the value of the subgrade Young's modulus, was developed to be a practical tool for the pavement engineer to use for evaluation and overlay design purposes. Detailed descriptions and listings of the computer programs SUBE and PAVEVAL are given in Appendixes A and B, respectively. Figure 2 gives a flow diagram of the general procedure used for pavement evaluation and overlay design.
Figure 2. Pavement evaluation and overlay design by the combined methods of layered elastic theory and vibratory nondestructive testing
GENERAL CONSIDERATIONS

The pavement parameters required by the computer programs SUBE and PAVEVAL are the Young's modulus, the Poisson's ratio, the thickness of the pavement layers and the subgrade, and the flexural strength for the PCC layers. Some progress has been made toward determining all of the elastic moduli of the pavement layers by vibratory nondestructive testing, but the results are not yet reliable. In this study, only the subgrade Young's modulus is obtained by vibratory nondestructive test methods.

Furthermore, the subgrade is assumed to be infinitely thick. Previous work on the design for PCC pavements incorporates a stiff layer 20 ft below the pavement surface. The present study found it unnecessary to incorporate a stiff layer at some arbitrary depth, so the computer programs SUBE and PAVEVAL assume a homogeneous subgrade.

The computer program PAVEVAL requires aircraft characteristics data as well as pavement parameters to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement. These data include the load on one main gear wheel, the total number of main gear wheels, the tire contact area, and the wheel spacings.

PAVEMENT LAYER THICKNESSES

The pavement layer thicknesses are obtained from construction drawings or from measurements of core samples and thicknesses in core holes in the existing pavement if no construction records are available.

POISSON'S RATIO

The Poisson's ratio of the wearing surface and base and subbase courses was chosen according to the rules $\nu = 0.2$ for PCC pavements, $\nu = 0.3$ for AC pavements and AC base materials, and $\nu = 0.35$ for all other base and subbase materials. The Poisson's ratio for all subgrade
soils is taken to be \( v = 0.35 \). Different choices for these variables can be made according to the type of materials present.

**YOUNG'S MODULUS**

The Young's modulus of the PCC wearing surface of the PCC pavement is taken to be \( 4.0 \times 10^6 \) psi. The temperature-dependent Young's modulus of AC pavements and AC base materials is obtained from Figure 3, corresponding to the pavement surface temperature at the time of the vibratory nondestructive testing. The temperature-dependent Young's modulus value is entered into the computer program SUBE to determine the subgrade Young's modulus. In this study, a value of \( E = 450,000 \) psi for AC pavements and AC base materials (corresponding to a yearly average temperature of 70°F) is entered into the computer program PAVEVAL that is to be compared with the conventional methods. However, in actual practice, a value of the AC Young's modulus is selected from the curve in Figure 3, representing the appropriate seasonal temperature.

The values of the Young's modulus of granular base and subbase materials can be estimated from the structure and composition of these materials. For instance, the laboratory resilient modulus test gives at least approximate values of the Young's modulus and the Poisson's ratio of these materials.\(^{13-15}\) A reasonable estimate of the values of Young's modulus of base and subbase materials can be obtained from Table 1. The subgrade Young's modulus that is entered into the computer program PAVEVAL is the Young's modulus value predicted by the computer program SUBE.

If the base and subbase materials are completely unknown, it is possible to use a trial-and-error procedure to obtain the values for the Young's moduli of these materials and the value of the subgrade Young's modulus by using the nonlinear computer program SUBE and the curves in Figure 4.

The procedure for estimating the values of the Young's moduli of the base and subbase courses is as follows:

a. Select a trial value of the subgrade Young's modulus.

b. Use Figure 4 to obtain the Young's moduli of the base and subbase courses.
Figure 3. Assumed temperature dependence of Young's modulus of AC pavements and AC base materials.
<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>( \text{Assigned Value of Young's Modulus} \times 10^3 \text{ psi} )</th>
<th>( \text{Assigned Value of Poisson's Ratio} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed limestone</td>
<td>Crushed limestone</td>
<td>80</td>
<td>0.35</td>
</tr>
<tr>
<td>GW</td>
<td>Well-graded gravel</td>
<td>60</td>
<td>0.35</td>
</tr>
<tr>
<td>GW-GM</td>
<td>GW and silty gravel</td>
<td>50</td>
<td>0.35</td>
</tr>
<tr>
<td>GP</td>
<td>Poorly graded gravel</td>
<td>40</td>
<td>0.35</td>
</tr>
<tr>
<td>GP-GC</td>
<td>GP and clayey gravels</td>
<td>35</td>
<td>0.35</td>
</tr>
<tr>
<td>SP</td>
<td>Poorly graded sand</td>
<td>30</td>
<td>0.35</td>
</tr>
<tr>
<td>SM</td>
<td>Silty sands, sand silt mixtures</td>
<td>30</td>
<td>0.35</td>
</tr>
<tr>
<td>SC</td>
<td>Clayey sands, sand clay</td>
<td>30</td>
<td>0.35</td>
</tr>
<tr>
<td>Black base</td>
<td>Mineral aggregate and bituminous material</td>
<td>Temperature dependent</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 4. Relationship between the Young's modulus of layer \( n \) and the Young's modulus of layer \( n + 1 \) for various thicknesses of layer \( n \)

c. Place these trial values of the Young's moduli of the base and subbase courses (along with the measured DSM) into the computer program SUBE and get a new value of the subgrade Young's modulus.

d. Use the new value of subgrade Young's modulus to get new values of the Young's moduli of the base and subbase courses from Figure 4.

e. Repeat the procedure to the accuracy desired.

FLEXURAL STRENGTH

The flexural strengths of the PCC material of wearing surfaces can be measured in the laboratory on specimens cored from the PCC
pavement. Splitting tensile tests are conducted, and the results are converted to flexural strengths. The approximate range of variation of the flexural strength of the PCC material found in the wearing surface of PCC pavements is $700 < R < 1020$ psi.

AIRCRAFT CHARACTERISTICS

Pavement evaluation and overlay design procedures must include characteristics of the types of aircraft that operate at an airport. Basic aircraft data must be entered into the PAVEVAL computer program in order to calculate the allowable load-carrying capacity and the required overlay thickness for a pavement. The required aircraft data include the load on one wheel, the tire contact area, the total number of main gear wheels, and the transverse and longitudinal wheel spacings. Table 2 gives the required data for several aircraft in common use.

The load on one wheel used in Table 2 takes into consideration the assumption that 5 percent of the gross aircraft weight is supported by the nose wheel. The load on one wheel is therefore given by: gross weight $\times 0.95$/number of main gear wheels. The operating load on a single wheel is used as the input load in the computer program PAVEVAL to calculate the overlay thickness for PCC and AC pavements. PAVEVAL automatically does the multiple-wheel calculation for the wheel configuration specified by the user.
Table 2. Aircraft Data

<table>
<thead>
<tr>
<th>Aircraft Gear Configuration or Model Designation</th>
<th>Typical Tire Contact Weight kips</th>
<th>Total No. of Main Gear Wheels</th>
<th>Load on One Wheel kips</th>
<th>Transverse Wheel Spacing in.</th>
<th>Longitudinal Wheel Spacing in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-wheel</td>
<td>30</td>
<td>190</td>
<td>2</td>
<td>14.25</td>
<td>--</td>
</tr>
<tr>
<td>Single-wheel</td>
<td>45</td>
<td>237</td>
<td>2</td>
<td>21.38</td>
<td>--</td>
</tr>
<tr>
<td>Single-wheel</td>
<td>60</td>
<td>271</td>
<td>2</td>
<td>28.50</td>
<td>--</td>
</tr>
<tr>
<td>Single-wheel</td>
<td>75</td>
<td>297</td>
<td>2</td>
<td>35.63</td>
<td>--</td>
</tr>
<tr>
<td>Dual-wheel</td>
<td>50</td>
<td>148</td>
<td>4</td>
<td>11.88</td>
<td>--</td>
</tr>
<tr>
<td>Dual-wheel</td>
<td>75</td>
<td>162</td>
<td>4</td>
<td>17.81</td>
<td>21</td>
</tr>
<tr>
<td>Dual-wheel</td>
<td>100</td>
<td>170</td>
<td>4</td>
<td>23.75</td>
<td>23</td>
</tr>
<tr>
<td>Dual-wheel</td>
<td>150</td>
<td>222</td>
<td>4</td>
<td>35.63</td>
<td>26</td>
</tr>
<tr>
<td>Dual-wheel</td>
<td>200</td>
<td>237</td>
<td>4</td>
<td>47.50</td>
<td>30</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>100</td>
<td>99</td>
<td>8</td>
<td>23.75</td>
<td>20</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>150</td>
<td>127</td>
<td>8</td>
<td>17.81</td>
<td>20</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>200</td>
<td>148</td>
<td>8</td>
<td>23.75</td>
<td>21</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>300</td>
<td>198</td>
<td>8</td>
<td>35.63</td>
<td>26</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>400</td>
<td>237</td>
<td>8</td>
<td>47.50</td>
<td>30</td>
</tr>
<tr>
<td>Boeing 727</td>
<td>173</td>
<td>210</td>
<td>4</td>
<td>41.09</td>
<td>34</td>
</tr>
<tr>
<td>DC-8-63F</td>
<td>358</td>
<td>220</td>
<td>8</td>
<td>42.51</td>
<td>32</td>
</tr>
<tr>
<td>Boeing 747</td>
<td>778</td>
<td>204</td>
<td>16</td>
<td>46.19</td>
<td>44</td>
</tr>
<tr>
<td>DC-10-10</td>
<td>433</td>
<td>294</td>
<td>8</td>
<td>51.42</td>
<td>54</td>
</tr>
<tr>
<td>DC-10-30</td>
<td>558</td>
<td>331</td>
<td>10</td>
<td>53.01</td>
<td>54</td>
</tr>
<tr>
<td>L-1011</td>
<td>428</td>
<td>282</td>
<td>8</td>
<td>50.83</td>
<td>52</td>
</tr>
<tr>
<td>Concorde</td>
<td>389</td>
<td>247</td>
<td>8</td>
<td>46.19</td>
<td>26.72</td>
</tr>
<tr>
<td>Boeing 737</td>
<td>111</td>
<td>174</td>
<td>8</td>
<td>13.18</td>
<td>30</td>
</tr>
<tr>
<td>Lockheed Electra</td>
<td>113</td>
<td>182</td>
<td>4</td>
<td>26.84</td>
<td>26</td>
</tr>
<tr>
<td>DC-9</td>
<td>115</td>
<td>165</td>
<td>4</td>
<td>27.31</td>
<td>25</td>
</tr>
<tr>
<td>Convair 880</td>
<td>188</td>
<td>152</td>
<td>8</td>
<td>22.33</td>
<td>22.5</td>
</tr>
<tr>
<td>Boeing 720</td>
<td>235</td>
<td>188</td>
<td>8</td>
<td>27.91</td>
<td>32</td>
</tr>
<tr>
<td>Boeing 707</td>
<td>336</td>
<td>218</td>
<td>8</td>
<td>39.90</td>
<td>34</td>
</tr>
</tbody>
</table>
LIMITING STRESS AND STRAIN CONDITIONS

As indicated previously, the failure of AC and PCC pavements can be related to limiting strain and stress conditions, respectively. Limiting stress and strain conditions are important for pavement evaluation because they relate the strain in the AC layer and the subgrade of AC pavements, and the stress in the PCC layer of PCC pavements, to the allowable load-carrying capacity and the required overlay thickness of a pavement. Because the stress and strain at any point in a pavement depends on the pavement structure, the limiting stress and strain concept relates the allowable load-carrying capacity and the required overlay thickness to the pavement structure, i.e., to the thickness and the elastic moduli of the pavement layers.

AC PAVEMENTS

The soil of the subgrade will undergo excessive plastic flow under repetitive loads if the repeated vertical strain at the top of the subgrade exceeds a limiting value. The limiting value of the vertical strain at the top of the subgrade depends on the number of strain repetitions and on the value of the Young's modulus of the soil in the subgrade. Figure 5 gives the limiting vertical strain $e_{VL}$ as a function of the subgrade Young's modulus for 1,200, 6,000, and 25,000 annual strain repetitions. The curves in Figure 5 are assumed to be valid for all types of subgrade soil and for single- and multiple-wheel loadings.

Figure 6 gives the limiting vertical strain at the top of the subgrade of AC pavements in terms of the total number of load repetitions independent of the value of the subgrade Young's modulus. A straight-line representation of the data in Figure 6 can be written as

$$\log e_{VL} = A \log N + B$$

where

- $e_{VL} =$ limiting vertical strain at the top of the subgrade
- $N =$ total number of load repetitions to failure
Figure 5. Limiting subgrade strain in terms of the subgrade Young's modulus for conventional AC pavements.
A best-fit curve through all the data in Figure 6 gives the values, \( A = -0.162 \) and \( B = -2.22 \), for the coefficients.

Figure 7 gives the limiting value of the tensile strain \( \varepsilon_{RL} \) at the bottom of the AC layer.\(^9\) The limiting vertical strain in the subgrade is found to be the controlling condition in most AC pavements, and for all cases considered in this study, it was found that the limiting vertical strain in the subgrade overshadowed the limiting tensile strain in the AC layer.

![Figure 7](image)

Figure 7. Limiting tensile strain at the bottom of the AC wearing surface

PCC PAVEMENTS

It is assumed that a load applied to the surface of a PCC pavement produces a maximum tensile stress at the bottom of the PCC layer. Further, cracking is assumed to occur first at the bottom of this layer. These are poor assumptions since failure often occurs at
the joints, and the location of the load or of curling conditions is not considered. This incipient cracking will probably be the onset of failure in a PCC pavement; it will begin in the PCC layer when the applied tensile stress at the bottom of this layer exceeds a limiting value of tensile stress.\textsuperscript{8,9} The limiting tensile stress is expressed in terms of the number of load (stress) repetitions and in terms of the flexural strength of the PCC layer as

\[ \sigma_{\text{RL}} = \frac{R}{A + B \log(COV)} \]  \hspace{1cm} (2)

where

\[ \sigma_{\text{RL}} = \text{limiting value of tensile stress, psi} \]
\[ R = \text{flexural strength, psi} \]
\[ A = 0.58901 \]
\[ B = 0.35486 \]
\[ COV = \text{number of coverages} \]

This expression is assumed to be valid whether the stress in the PCC layer is produced by a single- or a multiple-wheel loading.

The number of coverages is related to the number of load repetitions by a factor that depends on the type of aircraft operating on a runway. A coverage refers to a load covering the full width of the traffic lane and thus must be related to the number of repetitions of a particular gear configuration. The connection is made through a pass-to-coverage ratio \( \text{FAC} \), which is given by \( \text{FAC} = N/COV \) where \( N = \text{number of load repetitions} \). The limiting radial tensile stress given by Equation 2 can be expressed in terms of the number of load repetitions if the pass-to-coverage ratio is specified. Each gear configuration is associated with a unique value of the pass-to-coverage ratio. Table 3 gives values of the pass-to-coverage ratio for various gear configurations.\textsuperscript{16}
Table 3. Pass-to-Coverage Ratios

<table>
<thead>
<tr>
<th>Aircraft Wheel Configuration Type</th>
<th>Ratio (FAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>5.18</td>
</tr>
<tr>
<td>Dual</td>
<td>3.48</td>
</tr>
<tr>
<td>Dual-tandem</td>
<td>3.68</td>
</tr>
<tr>
<td>L-1011</td>
<td>3.62</td>
</tr>
<tr>
<td>B-747</td>
<td>3.70</td>
</tr>
<tr>
<td>DC-10-10</td>
<td>3.64</td>
</tr>
<tr>
<td>DC-10-30</td>
<td>3.38</td>
</tr>
<tr>
<td>DC-8</td>
<td>3.14</td>
</tr>
</tbody>
</table>
SUBGRADE YOUNG'S MODULUS DETERMINED BY VIBRATORY
NONDESTRUCTIVE TESTING OF PAVEMENTS

GENERAL considerations

The basic purpose of the vibratory nondestructive testing of pavements is to supply pavement parameters for the layered elastic theoretical calculation of the allowable load-carrying capacity and the required overlay thickness of a pavement. The layered elastic model of pavements requires the Young's modulus, the layer thickness, and the Poisson's ratio of the subgrade and pavement layers to be known. The elastic moduli of the pavement layers are estimated by various means, and only the subgrade Young's modulus is determined from vibratory nondestructive test results. The subgrade Young's modulus calculated by means of the computer program SUBE serves as an input pavement parameter for the layered elastic theory computer program PAVEVAL that is used for pavement evaluation and overlay design.

Pavements have been noted to behave nonlinearly under dynamic loadings.\(^1,3\) A nonlinear dynamic layered elastic theory and the computer program SUBE have been developed that determine the subgrade Young's modulus directly from the vibratory nondestructive test data measured at the pavement surface.\(^3,4\) The input pavement parameters for this dynamic elastic theory are the elastic modulus and the thickness of each pavement layer and the Poisson's ratio of the subgrade. The input from the vibratory nondestructive test data is the dynamic load-deflection curve measured at the surface of a pavement by the WES 16-kip vibrator.

The BISAR computer program is used for the design of PCC and AC pavements\(^9,12\) and has been modified for pavement evaluation and designated PAVEVAL.

VIBRATORY NONDESTRUCTIVE TEST DATA

The WES 16-kip vibrator applies a static load of 16 kips to the pavement surface and a dynamic load up to 15 kips at frequencies
ranging from 5 to 100 Hz. Both static and dynamic loads are applied to the pavement surface through a circular 18-in.-diam baseplate.

Four types of vibratory nondestructive tests are generally performed on pavements:

a. Dynamic load-deflection curves that show the dynamic deflection of the pavement surface as a function of the applied load for a fixed frequency of 15 Hz.

b. Frequency response spectrum that shows the dynamic deflection as a function of frequency for a fixed dynamic load.

c. Deflection basin measurements.

d. Rayleigh surface wave dispersion curves that show phase velocity versus wavelength (or frequency).

Only test a above is conducted and used in the method reported to determine the subgrade Young's modulus.

Figure 8 presents a typical dynamic load-deflection curve measured at 15 Hz. The dynamic deflection of the pavement surface is a nonlinear function of the dynamic load applied to the pavement surface. The slope of the dynamic load-deflection curve (tangent modulus) is called the DSM. The numerical value of the DSM is generally obtained from the region of high dynamic loading. Because the dynamic load-deflection curves are nonlinear, a nonlinear dynamic theory is required for their description and to extract the value of the subgrade Young's modulus.3,4

NONLINEAR DYNAMIC THEORY OF PAVEMENT RESPONSE

The nonlinear dynamic theory of pavement response was developed to describe the dynamic load-deflection curves that are measured at the pavement surface and to predict the value of the subgrade Young's modulus from the vibratory nondestructive test measurements.3,4 The nonlinear theory of pavement response develops and solves the equation of motion of a nonlinear oscillator and gives a theoretical expression for the dynamic deflection of the pavement surface in terms of the dynamic load applied to the pavement surface. The parameters that describe the nonlinear pavement response are related to the elastic moduli of the pavement layers and the subgrade.3 For a specified
Figure 8. Typical dynamic load-deflection curve for the AC pavement
choice of the elastic moduli of the pavement layers and the Poisson's ratio of the subgrade, the value of the subgrade Young's modulus is obtained by requiring that the theoretically predicted dynamic load-deflection curve agree with the measured dynamic load-deflection curve.\textsuperscript{3,4}

**DYNAMIC PAVEMENT RESPONSE COMPUTER PROGRAM SUBE**

The computer program SUBE calculates the value of the subgrade Young's modulus from input data taken from the measured dynamic load-deflection curves.\textsuperscript{4} The pavement input parameters for SUBE include the Young's modulus, the Poisson's ratio, and the thickness of each pavement layer, as well as the Poisson's ratio of the subgrade. The computer input that is taken from vibratory nondestructive test data is the DSM value and a point-by-point description of the measured dynamic load-deflection curve. From the DSM value, SUBE calculates the effective mass, the damping constant, the finite depth of influence of the static stress-strain field, and all the other parameters that enter into the nonlinear theoretical model of pavement response.\textsuperscript{4} SUBE iterates the value of the subgrade Young's modulus and determines the value of the subgrade Young's modulus that makes the theoretically predicted DSM value agree with the measured DSM value so that the theoretically predicted dynamic load-deflection curve will agree with the measured dynamic load-deflection curve. Figure 9 outlines the procedure.

**NUMERICAL VALUES OF THE PREDICTED SUBGRADE YOUNG'S MODULUS**

Tables 4 and 5 show the pavement structures for which dynamic load-deflection curves were measured. These tables also present the values of the elastic moduli of the pavement layers that were used in the computer program SUBE to predict the values of the subgrade Young's modulus. Figure 10 shows a comparison of the subgrade modulus values predicted by the nonlinear dynamic response theory through SUBE and the subgrade modulus values predicted by the formula \( E_s = 1500 \text{ CBR} \).\textsuperscript{17} The predicted subgrade Young's modulus values depend on the choice of the values of the Young's moduli of the pavement layers. No CBR or
Figure 9. Procedure for obtaining the subgrade Young’s modulus from the measured dynamic load-deflection curve.
Table 4. AC Pavement Structures Investigated

<table>
<thead>
<tr>
<th>Site</th>
<th>DSM (kips/in)</th>
<th>E₁ (psi)</th>
<th>v₁</th>
<th>h₁ (in)</th>
<th>E₂ (psi)</th>
<th>v₂</th>
<th>h₂ (in)</th>
<th>E₃ (psi)</th>
<th>v₃</th>
<th>h₃ (in)</th>
<th>Eₛ (WES)</th>
<th>vₛ</th>
<th>CBR</th>
<th>1500 CBR (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WES-WEL area subgrade</td>
<td>300</td>
<td>12,300</td>
<td>0.35</td>
<td>8</td>
<td>12,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Loess</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WES hangar No. 4 subgrade</td>
<td>400</td>
<td>10,700</td>
<td>0.35</td>
<td>31</td>
<td>44,500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lean + heavy clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TETS-adjacent subgrade</td>
<td>320</td>
<td>27,000</td>
<td>0.35</td>
<td>14</td>
<td>21,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lean clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TETS-poorhouse subgrade</td>
<td>300</td>
<td>15,900</td>
<td>0.35</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lean clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TETS-adjacent subgrade</td>
<td>450</td>
<td>13,000</td>
<td>0.35</td>
<td>8</td>
<td>12,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lean clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2A asphaltic concrete</td>
<td>700</td>
<td>230,000</td>
<td>0.35</td>
<td>5</td>
<td>230,000</td>
<td>0.35</td>
<td>7</td>
<td>32,000</td>
<td>0.35</td>
<td>9</td>
<td>25,000</td>
<td>0.35</td>
<td>14</td>
<td>21,000</td>
</tr>
<tr>
<td>WES test area asphaltic concrete</td>
<td>780</td>
<td>34,000</td>
<td>0.35</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GP</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>316 asphaltic concrete</td>
<td>770</td>
<td>1,400,000</td>
<td>0.35</td>
<td>3.25</td>
<td>1,400,000</td>
<td>0.35</td>
<td>3.25</td>
<td>34,000</td>
<td>0.35</td>
<td>6.0</td>
<td>29,600</td>
<td>0.35</td>
<td>18</td>
<td>27,000</td>
</tr>
<tr>
<td>Crushed limestone</td>
<td>780</td>
<td>30,000</td>
<td>0.35</td>
<td>6.0</td>
<td>200,000</td>
<td>0.35</td>
<td>24.0</td>
<td>6,700</td>
<td>0.35</td>
<td>4</td>
<td>6,000</td>
<td>0.35</td>
<td>4</td>
<td></td>
</tr>
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<td>300,000</td>
<td>860</td>
<td>180,000</td>
<td>0.35</td>
<td>9.0</td>
<td>180,000</td>
<td>0.35</td>
<td>9.0</td>
<td>40,000</td>
<td>0.35</td>
<td>5.0</td>
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<td>v&lt;sub&gt;1&lt;/sub&gt;</td>
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<td>E&lt;sub&gt;2&lt;/sub&gt;</td>
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<td></td>
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<th>in.</th>
<th>Classification</th>
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<th>$v_2$</th>
<th>in.</th>
<th>Classification</th>
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<td>PCC</td>
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<td>E-1(GW)</td>
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<td>E-4(SF-SM)</td>
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<td>E-7(ML-CL)</td>
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<td>3100</td>
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<td>8.0</td>
<td>E-6(ML)</td>
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Figure 10. Comparison of subgrade Young's modulus values predicted by the nonlinear dynamic theory computer program SUBE and by the wave propagation formula $E_s = 1500 \text{ CBR}$
coefficient of subgrade reaction values were measured for the subgrade at the PCC pavement sites.

The formula $E_s = 1500 \text{ CBR}$, where $E_s$ represents the subgrade Young's modulus, is obtained as a best-fit straight line through data points for which there was considerable scatter. Therefore, this relationship should be considered to be approximately true, and many deviations from the rule may occur according to the type of materials present and the extreme values of the CBR that may be encountered. The nonlinear dynamic theory of pavement response and the associated computer program SUBE were developed to predict values of the subgrade Young's modulus that are in reasonable agreement with the predictions of the formula $E_s = 1500 \text{ CBR}$. The predicted values of the subgrade Young's modulus can also be compared with laboratory resilient modulus measurements, but this comparison was not made in this study.

Some studies of the sensitivity of the predicted value of the subgrade Young's modulus on the choice of the value of the elastic moduli of the pavement layers have been conducted. Figure 11 shows the dependence of the predicted subgrade modulus values on the values of the Young's moduli of the pavement layers at a pavement site where the DSM value has been measured. The basic pavement structure about which the Young's modulus value of each pavement layer was varied one at a time is as follows:

$E_1 = 200,000 \text{ psi}$ $h_1 = 5.0 \text{ in.}$
$E_2 = 80,000 \text{ psi}$ $h_2 = 7.0 \text{ in.}$
$E_3 = 40,000 \text{ psi}$ $h_3 = 9.0 \text{ in.}$
Figure 11. Dependence of the subgrade Young's modulus values predicted by the computer program SUBE on the chosen values of the Young's modulus of the wearing surface and the base and subbase courses.
GENERAL CONSIDERATIONS

The determination of the load-carrying capacity of a pavement and the overlay thickness required to upgrade a pavement entails the calculation of the vertical compressive strain at the top of the subgrade or the tensile strain at the bottom of the AC layer for AC pavements, and the tensile stress at the bottom of the PCC layer for PCC pavements. The calculation of the stress and the strain at points in the pavement and the subgrade is accomplished by modeling the pavement and the subgrade as a semi-infinite layered elastic halfspace for which each layer is described by a Young's modulus, a Poisson's ratio, and a thickness. The layered elastic theory connects the allowable load at the pavement surface and the required overlay thickness for PCC pavements with the limiting values of tensile stress at the bottom of the PCC layer; and for AC pavements, with the compressive vertical strain at the top of the subgrade or the tensile strain at the bottom of the AC layer. The BISAR computer program is used to implement the basic layered elastic theory.

The input parameters for the layered elastic theoretical model of a pavement are the elastic moduli and the thickness of each pavement layer. As discussed previously, the subgrade Young's modulus can be obtained from vibratory nondestructive tests conducted at the surface of the pavement, and the Young's modulus of the wearing surface and the base and subbase courses can be obtained from a classification of the material or from the measured CBR. The thicknesses of the pavement layers are obtained from construction specifications or from measurements in the field. Therefore, all of the parameters required by the layered elastic theory are available for pavement structures.

BISAR COMPUTER PROGRAM

The BISAR computer program was developed by the Shell Oil Company for pavement applications. This computer program calculates the stress
and the strain at any point in the pavement or the subgrade due to a loading at the pavement surface. Particle displacements, stresses, and strains are obtained by numerical integration.

Boundary conditions between the pavement layers may be taken to be rough or smooth. For the rough condition, the radial and tangential stresses and strains are continuous across the layer interfaces. For the smooth condition, the radial and tangential stresses and strains are not continuous across the interface. For PCC pavements, the interface between the PCC wearing surface and the base is assumed to be smooth, while all other interfaces are taken to be rough. For AC pavements, all interfaces are assumed to be rough.

Each pavement layer is characterized by a thickness, a Poisson’s ratio, and a Young’s modulus. Therefore, three parameters must be specified for each pavement layer. The value of the surface load and the size of the circular loaded area must be specified. The coordinates of the point in the pavement where the stress and the strain are to be calculated must also be specified. The BISAR computer program has the capability of calculating the stress and the strain in the pavement when more than one load is applied to the pavement surface.

The BISAR computer program is modified to calculate the overlay thickness required to upgrade a pavement and the allowable load-carrying capacity of a pavement. The modification consists of an iterative procedure to match the calculated stress and strain with specified limiting values of the stress and the strain. The resulting computer program is called PAVEVAL.
ALLOWABLE LOAD-CARRYING CAPACITY AND
REQUIRED OVERLAY THICKNESS OF PAVEMENTS

GENERAL CONSIDERATIONS

The allowable load-carrying capacity and the required overlay thickness of a pavement is related to the pavement structure. The layered elastic theory relates the allowable load-carrying capacity and the required overlay thickness to the pavement structure as represented by the elastic modulus and the thickness of each pavement layer. The following paragraphs describe the layered elastic method of pavement evaluation and overlay design.

CHOICE OF ELASTIC MODULI FOR PAVEVAL COMPUTER PROGRAM

The value of the subgrade Young's modulus that is used in the PAVEVAL computer program to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement is obtained by using the computer program SUBE to analyze the dynamic load-deflection curves measured at a pavement site. The choice of the elastic moduli of the pavement layers that are entered into PAVEVAL are the same as those selected for SUBE with the exception that the Young's modulus of AC pavements and AC base materials is chosen always to have the value \( E = 450,000 \text{ psi} \) in PAVEVAL. This value of the Young's modulus is obtained from Figure 3, corresponding to an assumed average yearly pavement temperature of 70°F.

The values of the Young's modulus of AC pavements and AC base materials that are used in the computer program SUBE to calculate the subgrade Young's modulus are obtained from Figure 3 for a temperature equal to the pavement temperature at the time of the measurement of the dynamic load-deflection curves.

SINGLE-WHEEL LOADING

A point in the pavement and the subgrade is designated to have coordinates \( x, y, z \), where \( x \) and \( y \) describe the horizontal plane and \( z \) measures the depth beneath the pavement surface (Figure 12). The
The vertical strain $\epsilon_v$, the tensile strain $\epsilon_R$, and the radial stress $\sigma_R$ at a point in the pavement are functions of the coordinates of the point in the manner $\epsilon_v = \epsilon_v(x,y,z)$, $h = h(x,y,z)$, $\sigma_R = \sigma_R(x,y,z)$. The maximum values of the stress and the strain in the pavement and the subgrade occur directly beneath the single-wheel load, so that if a coordinate system is chosen whose origin is at the center of the single-wheel load, as shown in Figures 12 and 13, the vertical strain at the top of the subgrade, the radial strain at the bottom of the AC layer, and the tensile stress at the bottom of the FCC layer are represented by

$$H_s = h_1 + h_2 + h_3 = \text{DEPTH TO TOP OF SUBGRADE}$$

Figure 12. Coordinate system chosen for the layered elastic theory of pavements.
Figure 13. Calculation of the stress and the strain for a single-wheel loading

\[ \begin{align*}
\varepsilon_y &= \varepsilon_y(0, 0, H_s) \\
\varepsilon_R &= \varepsilon_R(0, 0, h_1) \\
\sigma_R &= \sigma_R(0, 0, h_1)
\end{align*} \]

AC PAVEMENT

PCC PAVEMENT
where
\[ H_b = \text{depth to the top of the subgrade of an AC pavement} \]
\[ h_1 = \text{thickness of a PCC or an AC wearing surface} \]

The conditions that determine the allowable load-carrying capacity and the required overlay thickness are

\[ \varepsilon_V = \varepsilon_V \left(0,0,H_b\right) \] (3)

\[ \varepsilon_R = \varepsilon_R \left(0,0,h_1\right) \] (4)

\[ \sigma_R = \sigma_R \left(0,0,h_1\right) \] (4)

MULTIPLE-WHEEL LOADING

Actual aircraft loadings on a pavement occur through two or more wheels in close proximity. Dual-gear (two wheels) and dual-tandem-gear (four wheels) configurations are commonly used. As indicated in Figure 14, a total number of four main gear wheels are associated with two dual-gear configurations, and eight main gear wheels with two dual-tandem-gear configurations. For the case of multiple wheels, the total strain or stress in the pavement beneath one wheel is due in part to the presence of the other wheels. The maximum values of the stress and the strain at some depth in the pavement occur at a point between the wheels of the gear configuration, but these maximum values of the stress and the strain in the pavement are to a good approximation equal to the values of the stress and the strain in the pavement beneath one of the wheels of a multiple-wheel configuration. The multiple-wheel
DUAL WHEELS

\[
\begin{align*}
\sigma_{RD} &= \sigma_{RD}(0,0,h_1) \\
\varepsilon_{RD} &= \varepsilon_{RD}(0,0,h_1) \\
\varepsilon_{VD} &= \varepsilon_{VD}(0,0,H_5)
\end{align*}
\]

PCC PAVEMENT

AC PAVEMENT

DUAL-TANDEM WHEELS

\[
\begin{align*}
\sigma_{RDT} &= \sigma_{RDT}(0,0,h_1) \\
\varepsilon_{RDT} &= \varepsilon_{RDT}(0,0,h_1) \\
\varepsilon_{VDT} &= \varepsilon_{VDT}(0,0,H_5)
\end{align*}
\]

PCC PAVEMENT

AC PAVEMENT

Figure 14. Calculation of the total stress and strain for dual and dual-tandem wheels
calculations are made within this approximation. The calculation of
the allowable load-carrying capacity and the required overlay thickness
must include the additive stress and strain effects associated with
multiple-wheel loadings.

The effects of multiple-wheel loadings are accounted for by
calculating the net stress and strain in the pavement or the subgrade
under a selected wheel and by adding the stress and strain components
of the remaining wheels occurring under the selected wheel. The BISAR
computer program calculates the stress and the strain in a pavement at
any depth directly under one wheel due to the action of the wheel loads
applied at the pavement surface. For dual wheels, let

\[ \varepsilon_{VD} = \text{total vertical strain at a point in the pavement}
\]
\[ \text{directly under one wheel at the top of the subgrade}
\]
\[ \text{for AC pavements} \]
\[ \varepsilon_{RD} = \text{total radial strain under one wheel at the bottom}
\]
\[ \text{of the AC pavement layer} \]
\[ \sigma_{RD} = \text{total radial stress at the bottom of the PCC layer}
\]
\[ \text{at a point under one wheel} \]

For dual-tandem wheels, let

\[ \varepsilon_{VDT} = \text{total vertical strain at the top of the subgrade}
\]
\[ \text{for AC pavements at a point directly under one}
\]
\[ \text{wheel} \]
\[ \varepsilon_{RDT} = \text{total radial strain at the bottom of the AC}
\]
\[ \text{pavement layer at a point under one wheel} \]
\[ \sigma_{RDT} = \text{total radial stress at the bottom of the PCC}
\]
\[ \text{layer at a point under one wheel} \]

For dual wheels, the conditions that determine the allowable
load-carrying capacity and the required overlay thickness are

\[ \varepsilon_{VD} (0,0,h_1) = \varepsilon_{VL} \]  
[AC pavements]  
(7)
\[ \varepsilon_{RD} (0,0,h_1) = \varepsilon_{RL} \]  
[PCC pavements]  
(8)

while for dual-tandem wheels the conditions are

\[ h_1 \]
\[
\begin{align*}
\epsilon_{\text{VDT}} (0,0,h_s) &= \epsilon_{\text{VL}} \\
\epsilon_{\text{RDT}} (0,0,h_1) &= \epsilon_{\text{RL}} \\
\sigma_{\text{RDT}} (0,0,h_1) &= \sigma_{\text{RL}}
\end{align*}
\]

AC pavement \hspace{1cm} (9)

PCC pavement \hspace{1cm} (10)

The limiting stress and strain values do not depend on the type of surface loading and are valid for single- and multiple-wheel loadings.

ALLOWABLE LOAD-CARRYING AND REQUIRED OVERLAY THICKNESS FOR AC AND PCC PAVEMENTS

For AC and PCC pavements, the allowable load-carrying capacity is calculated by monitoring the stress and the strain at points in the pavement indicated in Figure 15. The PAVEVAL computer program has the capability of iterating the wheel load at the pavement surface for a given pavement structure until the calculated value of the vertical strain at the top of the subgrade of an AC pavement is equal to the limiting value of the vertical strain or until the calculated value of the tensile strain at the bottom of the AC layer is equal to the limiting value of the tensile strain, as shown in Figures 5, 6, and 7. The calculated value of the tensile stress at the bottom of the AC layer must equal the limiting value of the tensile stress as given in Equation 2. This determines the allowable load-carrying capacity for AC and PCC pavements.

The required overlay thickness for AC and PCC pavements is calculated by examining the stress and the strain at points in the pavement indicated in Figure 16. The PAVEVAL computer program can be used to iterate the thickness of the overlay for a wheel load until the calculated value of the vertical strain at the top of the subgrade of an AC pavement is equal to or less than the limiting value of the vertical strain and until the calculated value of the tensile strain at the bottom of the AC layer is equal to or less than the limiting value of the tensile strain. For PCC pavements, the calculated value of the tensile stress at the bottom of the PCC layer must equal the limiting value of the tensile stress.
1 POINT WHERE TENSILE STRESS AND TENSILE STRAIN IS MONITORED FOR A PCC OR AN AC WEARING SURFACE

2 POINT WHERE VERTICAL COMPRESSION STRAIN IS MONITORED FOR AN AC WEARING SURFACE

Figure 15. Location of points where the total stress and strain are monitored for the calculation of the allowable load-carrying capacity of AC and PCC pavements
Figure 16. Location of points where the total stress and strain are monitored for the calculation of the required overlay thickness.
NUMERICAL VALUES OF THE ALLOWABLE LOAD-CARRYING CAPACITY AND THE REQUIRED OVERLAY THICKNESS

The pavement evaluation procedures discussed previously were applied to a number of PCC and AC pavement structures for single- and multiple-wheel loadings, and the allowable load-carrying capacity and the required overlay thickness were calculated by combining the layered elastic theory with inputs from vibratory nondestructive testing. For these pavement structures, the allowable load-carrying capacity and the required overlay thickness were also calculated by the conventional CBR and DSM methods for AC pavements and by the Westergaard and DSM methods for PCC pavements.

Tables 6-17 present the predicted values of the allowable load-carrying capacity and the required overlay thickness for the AC and PCC pavement sites whose structures appear in Tables 4 and 5. In these tables, the load-carrying capacity is expressed in terms of the load on one wheel. The total allowable airplane load is obtained by the expression: (allowable load on one wheel) \times (total number of main gear wheels)/0.95. Single-wheel, dual-wheel, and dual-tandem-wheel gear configurations were considered. The total number of main gear wheels for these configurations are 2, 4, and 8, respectively. Specific calculations were done for the single-wheel load, the Boeing 727 (dual wheels), the DC-8-63F (dual-tandem wheels), and the DC-10-10 (dual-tandem wheels).

For AC pavements, Figures 17 and 18 compare the layered elastic theory calculation of the allowable load on one wheel and the required AC overlay thickness with the corresponding CBR calculation of these quantities. For PCC pavements, Figures 19 and 20 compare the results of the layered elastic theory calculation of the allowable load on one wheel and the AC and PCC required overlay thickness with the results of the corresponding Westergaard calculations of these quantities. Reference 1 describes the CBR and Westergaard methods of calculating the allowable load and the overlay thickness, respectively, for AC and PCC pavements. The data plotted in Figures 17-21 correspond to the data presented in Tables 6-17.
Table 6. Allowable Load (Layered Elastic Theory Method) of AC Pavement, 1200 Annual Strain Repetitions

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<th>Site</th>
<th>Measured DSM kips/in.</th>
<th>Temperature* Adjusted DSM kips/in.</th>
<th>Allowable Load on One Wheel (Single Wheel) kips</th>
<th>Allowable Load on One Wheel (Dual Wheels) Boeing 727 kips</th>
<th>Allowable Load on One Wheel (Dual-Tandem Wheels) kips</th>
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* From Reference 1.
Table 7. Allowable Load (CBR Method) of AC Pavement, 1200 Annual Strain Repetitions

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### Table 8. Allowable Load (DSM Method) of AC Pavement, 1200 Annual Strain Repetitions

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* From Reference 1.
Table 7. Allowable Load (CBR Method) of AC Pavement,
1200 Annual Strain Repetitions

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* From Reference 1.
Table 9. Required Overlay Thickness (Layered Elastic Theory Method) of AC Pavement, 1200 Annual Strain Repetitions

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* From Reference 1.
Table 11. Required Overlay Thickness (DSM Method) of AC Pavement, 1200 Annual Strain Repetitions

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<th>R (psi)</th>
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<th>Allowable Load on One Wheel (Dual Wheels) Boeing 727 (kips)</th>
<th>Allowable Load on One Wheel (Dual-Tandem Wheels) DC-8-63F</th>
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<th>Allowable Load on One Wheel (Dual Wheels) Boeing 727 kips</th>
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<th>Allowable Load on One Wheel (Dual Wheels) Boeing 727 kips</th>
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Table 13 (Concluded)
Table 14. Allowable Load (DSM Method) of PCC Pavement, 1200 Annual Stress Repetitions

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<th>Allowable Load on One Wheel (Dual Wheels) Boeing 727 kips</th>
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<th>Allowable Load on One Wheel (Dual Wheels) kips</th>
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### Table 15. Required Overlay Thickness (Layered Elastic Theory Method) at IRC Pavement, 1200 Annual Stress Repetition.

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Table 15 (Concluded)

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<th>Required Overlay Thickness (Dual-Wheel Load) Boeing 727 in.</th>
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<td>SWL = 41,090 lb</td>
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Table 16. Required Overlay Thickness (Westergaard Method) of PCC Pavement, 1200 Annual Stress Repetitions

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<th>Measured DSM kips/in.</th>
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<th>Required Overlay Thickness (Dual-Wheel Load) Boeing 727 in.</th>
<th>Required Overlay Thickness (Dual-Tandem-Wheel Load) in.</th>
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<td></td>
<td>SWL = 35,625 lb</td>
<td>SWL = 41,090 lb</td>
<td>DC-8-63F SWL = 42,510 lb DC-10-10 SWL = 51,420 lb</td>
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Table 16 (Concluded)

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<th>Required Overlay Thickness (Dual-Wheel Load) Boeing 727 in.</th>
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Table 17. Required Overlay Thickness (DSM Method) of PCC Pavement, 1200 Annual Stress Repetitions

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<th>Required Overlay Thickness (Dual-Wheel Load) Boeing 727 in.</th>
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Figure 17. Allowable load-carrying capacity of AC pavements calculated by the layered elastic theory and by the CBR and DSM methods.
Figure 18. AC required overlay thickness for AC pavements calculated by the layered elastic theory and by the CBR and DSM methods.
Figure 19. AC and PCC required overlay thicknesses for PCC pavements calculated by the layered elastic theory and the Westergaard method.
Figure 20. AC and PCC required overlay thicknesses for PCC pavements calculated by the layered elastic theory and the DSM method.
Figure 21. Allowable load-carrying capacity of PCC pavements calculated by the layered elastic theory and by the DSM and Westergaard methods.
For some AC pavements, the layered elastic theory method predicts values of allowable loads that are larger than the aircraft loads, while the DSM method predicts allowable load values that are less than the aircraft load (Tables 6 and 8 and Figure 17). For these cases, the values of the required overlay thicknesses predicted by the layered elastic theory method are zero while those predicted by the DSM method have nonzero values (Figure 18).
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The capability of determining the load-carrying capacity of a pavement and the overlay thickness required to upgrade a pavement is important to pavement engineers. A simple method of pavement evaluation combining vibratory nondestructive field tests with a layered elastic theory was developed to satisfy the needs of the pavement engineer. The layered elastic theory approach to calculating the required overlay thickness and the load-carrying capacity of a pavement requires the value of the subgrade Young's modulus, and this value is determined by an analysis of the pavement dynamic response obtained from vibratory nondestructive testing. This approach requires a knowledge of the structure of the pavement and the subgrade as described by the elastic modulus, the Poisson's ratio, and the thickness of each pavement layer.

The method of pavement evaluation presented consists of two parts: (a) the determination of the subgrade Young's modulus from vibratory nondestructive tests that measure the pavement response to an applied dynamic load, and (b) the use of the layered elastic theory and the determined value of the subgrade Young's modulus to predict the allowable load-carrying capacity and the required overlay thickness of a pavement. Two computer programs, SUBE and PAVEVAL, are used to evaluate a pavement based on vibratory nondestructive tests and the layered elastic theory.

The computer program SUBE determines the value of the subgrade Young's modulus from the measured dynamic load-deflection curves and the estimated values of the elastic moduli and thicknesses of the pavement layers. The mathematical model on which SUBE is based is a non-linear harmonic oscillator whose predicted dynamic load-deflection curve is matched to the measured dynamic load-deflection curves in order to determine the value of the subgrade Young's modulus. The predicted values of the subgrade Young's modulus are in essential agreement with the formula $E_s = 1500$ CBR and are not especially sensitive to the choice of the elastic moduli of the pavement layers.
The computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness values for the layered elastic theory by relating the stress and the strain at any point in the pavement or subgrade to the magnitude of the static load applied to the pavement surface. The elastic moduli, Poisson's ratios, and thicknesses of the pavement layers and the subgrade must be known to use this computer program. For PCC, the flexural strength must also be known. Aircraft parameters including the load on one wheel, the tire contact area, wheel spacings, and the total number of main gear wheels are also required for PAVEVAL.

CONCLUSIONS

The study of predicting pavement performance and overlay design by the combined techniques of layered elastic theory and vibratory nondestructive testing yielded the following conclusions:

a. The layered elastic theory method using the subgrade Young's modulus determined from the results of vibratory nondestructive tests is sufficient to predict the allowable load-carrying capacity and the required overlay thickness for a pavement; computer programs SUBE and PAVEVAL have been developed to aid in pavement evaluation and overlay design.

b. The value of the subgrade Young's modulus can be obtained from vibratory nondestructive test results through the use of the computer program SUBE.

c. Limiting stress and strain criteria can be used in conjunction with the layered elastic theory to determine the allowable load-carrying capacity and the required overlay thickness of a pavement. This can be determined for dual-wheel and dual-tandem-wheel loads, as well as for single-wheel loads, by using the computer program PAVEVAL.

RECOMMENDATIONS

A method has been developed for calculating the allowable load-carrying capacity and the required overlay thickness for pavements by using the combined methods of layered elastic theory and vibratory nondestructive testing. The accuracy of these calculations depends in part on the accuracy of the predicted values of the subgrade Young's
modulus. Further experimental work is necessary to validate the predicted pavement evaluations, overlay designs, and values of the subgrade Young's modulus.

DETERMINATION OF SUBSURFACE STRUCTURE

The determination of the subgrade Young's modulus by the vibratory nondestructive testing technique requires a knowledge of the elastic moduli of the pavement layers above the subgrade. The determination of the allowable load-carrying capacity of a pavement by the layered elastic theory method requires the elastic moduli of all pavement layers as well as the Young's modulus of the subgrade. Therefore, the Young's moduli of the pavement layers are used twice in the procedure for calculating the allowable load-carrying capacity of a pavement. In view of this, it is recommended that:

a. Vibratory nondestructive tests be developed that will accurately determine the values of the Young's moduli of all pavement layers.
b. A reliable method be developed to estimate the Young's modulus of the material in each pavement layer in terms of its composition and structure.

STATIC LOAD TESTS

Static load tests are required for the conventional evaluation of PCC and AC pavements. These tests determine the CBR for the AC pavement evaluation and the coefficient of the subgrade reaction for the PCC evaluation using the Westergaard theory. It is recommended that static load tests and vibratory nondestructive tests be performed at a number of pavement sites so that further comparisons can be made.

LABORATORY CONFIRMATION OF FIELD TEST DATA

A complete connection between the resilient modulus laboratory tests and the vibratory nondestructive field tests has not yet been accomplished. However, the results of a preliminary theoretical study show that it is possible to apply a nonlinear dynamic theory to the resilient modulus laboratory test to determine the static elastic
Young's modulus of a subgrade soil and to compare this value with the Young's modulus value predicted by the nonlinear dynamic analysis of the vibratory nondestructive field test data and with the Young's modulus predicted by the formula $E_s = 1500$ CBR. It is recommended that resilient modulus tests be conducted on undisturbed soil samples taken at sites where vibratory nondestructive tests have been conducted.
REFERENCES


APPENDIX A: COMPUTER PROGRAM SUBE

The evaluation of rigid and flexible pavements by the combined methods of vibratory nondestructive testing and layered elastic theory requires two computer programs. The computer program SUBE calculates the value of the subgrade Young's modulus from the dynamic load-deflection curves measured at the pavement surface and from the chosen values of the elastic moduli of the pavement layers.

DOCUMENTATION OF THE COMPUTER PROGRAM SUBE

PROGRAM IDENTIFICATION
a. Program Title. WES Nonlinear Dynamic Load-Deflection Program
b. Program Code Name. SUBE
c. Writer. Richard A. Weiss and Adrian P. Park
d. Organization. U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180
e. Date. July 1977
f. Source Language. Fortran IV
g. Abstract. Program calculates the value of the subgrade Young's modulus by requiring a nonlinear dynamic pavement response model to agree with the measured dynamic load-deflection curves.

ENGINEERING DOCUMENTATION

Narrative Description. The pavement and subgrade are modeled as a nonlinear harmonic oscillator with third-order and fifth-order nonlinear terms. The inertial and damping characteristics of the pavement are introduced by an effective pavement mass and a damping constant. These model parameters are expressed in terms of the measured DSM of the pavement. The elastic characteristics of the pavement and subgrade are represented by the Young's moduli and Poisson's ratios of the pavement layers.

Method of Solution. The solution of a nonlinear harmonic oscillator model of pavement response is determined in terms of the elastic moduli and thicknesses of the pavement layers, the effective

A-1
mass of the pavement, the damping constant, and the assorted nonlinear model parameters. The value of the subgrade Young's modulus is obtained by matching the theoretical solution for the dynamic load-deflection curve with the measured value of the dynamic load-deflection curve. The computer program SUBE is used to calculate the subgrade Young's modulus. This computer program iterates the value of the subgrade Young's modulus until the theoretically predicted dynamic load-deflection curve agrees with the measured dynamic load-deflection curve; the value of the subgrade Young's modulus that brings agreement between its measured and theoretical load-deflection curves is the subgrade Young's modulus value that is printed out by the program SUBE.

Program Capabilities. The program calculates the subgrade Young's modulus from dynamic load-deflection curves measured on either flexible or rigid pavements. Rigid and flexible pavements can be handled by entering the appropriate values of the elastic moduli of the wearing surface. The computer program SUBE is valid only for a limited range of measured dynamic load-deflection curves. The DSM is the slope of the measured dynamic load-deflection curve for a dynamic load \( F_D = 15 \text{ kips} \). The computer program SUBE gives valid predictions of the subgrade Young's modulus only within the range \( 300 < \text{DSM} < 6500 \text{ kips/in.} \)

Printed Output. The printed output consists of the predicted value of the subgrade Young's modulus.

Computer Equipment. The program SUBE was developed on the IBM 360/65 computer.

INPUT GUIDE FOR COMPUTER PROGRAM SUBE

The input for the computer program SUBE is the elastic moduli and thicknesses of the pavement layers, the measured DSM, and a point-by-point description of the measured dynamic load-deflection curve. The point-by-point description of the measured dynamic load-deflection curve is entered into SUBE by means of a data file. The
elastic constants, layer thicknesses, and the measured DSM value are entered into the main body of the computer program. This is done as follows:

2360 Measured DSM value (kips/in.)
2365 Enter 0.0 if dynamic load-deflection curve is straight and 1.0 if dynamic load-deflection curve is curved
5240 Poisson's ratio of layer 1
5250 Poisson's ratio of layer 2
5260 Poisson's ratio of layer 3
5270 Poisson's ratio of layer 4
5300 Young's modulus of layer 1, psi
5310 Young's modulus of layer 2, psi
5320 Young's modulus of layer 3, psi
5330 Initial value of Young's modulus of subgrade, psi
5340 Iteration statement for Young's modulus of subgrade
5580 Thickness of layer 1, in.
5590 Thickness of layer 2, in.
5600 Thickness of layer 3, in.

INPUT GUIDE FOR DATA FILE FOR SUBE

010 9000

Dynamic Load, kips Dynamic Deflection, mils

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014 3 "
016 6 "
018 8 "
020 10 "
022 12 "
024 14 "

SAMPLE PROBLEM USING PROGRAM SUBE

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RUN

NAME OF DATA FILE? N23

PROGRAM LISTING

A complete listing of the computer program is presented on the following pages.
COMPUTER PROGRAM SUBE CALCULATES THE VALUE OF THE SUBGRADE YOUNG'S MODULUS FROM THE DYNAMIC LOAD-DEFLECTION CURVES MEASURED AT THE PAVEMENT SURFACE. THIS IS DONE BY REQUIRING THE THEORETICAL RESULTS OF A NONLINEAR RESPONSE MODEL FOR THE PAVEMENT TO AGREE WITH THE MEASURED DYNAMIC LOAD-DEFLECTION CURVES.

THE SUBPROGRAM POLFIT FITS LEAST-SQUARES POLYNOMIALS TO BIVARIATE DATA. IT IS APPLIED TO THE MEASURED DYNAMIC LOAD-DEFLECTION CURVES IN THE FORM OF AN ODD ORDER POLYNOMIAL HAVING LINEAR, CUBIC AND FIFTH ORDER TERMS.
52: M77=M7/M
53: T77=T7/M
54: T99=SQRT(T9)
55: 314 FORMAT(///,'LEAST SQUARES POLYNOMIALS',/,
56: &//,7X,'NUMBER OF POINTS =',12,//,7X,'MEAN VALUE OF X =',1PE14.6, 
57: &//,7X,'MEAN VALUE OF Y =',1PE14.6,//,7X,'STD ERROR OF Y =', 
58: &/1PE14.6)
59: C
60: DO 352 I=1,M
61: P(I)=Z
62: 352 Q(I)=0
63: DO 362 I=1,11
64: 362 A(I)=Z 
65: B(I)=Z
66: S(I)*Z
67: E1=Z
68: F1=Z
69: W1=M
70: N4+K
71: K1=Z
72: IF(N.E.0) K1=N4
73: 380 H=Z
74: DO 386 L=1,M
75: 386 M=M*Y(L)*Q(L)
77: S(J)*M/W1
78: IF(J-4.GE.0.OR.I-M.GE.0) GO TO 428
79: E1=Z
80: DO 398 L=1,M
81: E1=E1+X(L)*Q(L)*Q(L)
82: E1=E1+W1
83: A(I+1)=E1
84: W=Z
85: DO 416 L=1,M
86: V=(X(L)-E1)*Q(L)*F1*P(L)
87: P(L)=Q(L)
88: Q(L)=V
89: 416 W=W+V*V
90: F1=W/W1
91: B(I+2)=F1
92: W=H
93: I=I+1
94: GO TO 380
95: 428 DO 432 L=1,12,1
96: 432 G(L)=Z
97: G(I)=0
98: DO 464 J=1,M
99: S1=Z
100: DO 448 L=1,1,N
101: IF(L.NE.11G(L)*G(L)-A(L)*G(L-1)
102: IF(L.GT.2G(L)*G(L)-B(L)*G(L-2)
103: 448 S1=S1+S(L)*Q(L)
104: U(J)=S1

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105* L=N
106* DO 460 I2=2,N
107* G(L)=G(L-1)
108* L=1-I
109* 460 CONTINUE
110* G(I)=Z
111* 464 CONTINUE
112* T=Z
113* CONTINUE
114* I2=2,N
115* J=I-1
116* DO 462 I2=1,N
117* C(L)=C(L)*X(L)+U(I)
118* J=I-1
119* 462 CONTINUE
120* T3=Y(L)-C(L)
121* T=T+T3*T3
122* 488 CONTINUE
123* IF(M.NE.N) GO TO 496
124* TS=T/(M-N)
125* Q7T=-T/(T9*fM-1))
126* IF(M.NE.99) GO TO 548
127* ITEMP*N-1
128* PRINT 500,ITEMP,Q7
129* 500 FORMAT(/,'POLVFIT OF DEGREE ','INDEX OF DETERM = ',
130* &1PE14.6)
131* PRINT 516
132* 516 FORMAT(/,' TERM','8X','COEFFICIENT',/)
133* DO 526 J=1,N
134* I2=J-1
135* 526 PRINT 527,I2,Ui)
136* 527 FORMAT(14,2X,1PE14.7)
137* PRINT 530
138* 530 FORMAT(/,' X-ACTUAL','12X','Y-ACTUAL','3X','Y-CALC','8X','DIFF',
139* &8X,'PCT-DIFF',/)
140* DO 550 L=1,M
141* QB=Y(L)-C(L)
142* IF(C(L)-0.0) QB=0.0
143* 550 CONTINUE
144* PRINT 551,X(L),Y(L),C(L),QB,0.88
145* GO TO 550
146* 548 PRINT 552,X(L),Y(L),C(L),QB
147* 550 CONTINUE
148* 551 FORMAT(1PE14.6)
149* 552 FORMAT(1PE14.6,3X,'INFINITE')
150* 555 CONTINUE
151* 555 FORMAT(/,'STD ERROR OF ESTIMATE FOR Y = ',1PE14.6)
152* C
153* C THIS IS THE END OF THE PART POLFT

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158 C TO ELIMINATE THE DIFFICULTIES ASSOCIATED WITH THE USE OF
159 C LARGE NUMBERS THE INTERNAL CALCULATIONS OF THIS PROGRAM
160 C ARE DONE IN THE UNITS LISTED AS FOLLOWS, BUT THE UNITS
161 C OF THE INPUT DATA ARE IN INCHES
162 C
163 C UNITS OF MASS - KIP-SEC**2/MILL
164 C UNITS OF WEIGHT - KIP
165 C UNITS OF DAMPING - KIP-SEC/MILL
166 C UNITS OF DYNAMIC STIFFNESS - KIP/MILL
167 C UNITS OF NONLINEAR COEFF. B - KIP/MILL**3
168 C UNITS OF NONLINEAR COEFF. E - KIP/MILLWMS
169 C
170 C 789 CONTINUE
171 A-8
A-9
264 BC2=0.02
265 DEL=0.001
266 BC1=15.0
267 IF(DSMH-3500)144,144,144
268 144 CONTINUE
269 CD0=-7.9887704E-05
270 CD1=6.3085251E-04
271 CD2=-7.4214518E-06
272 CD3=-1.1141749E-05
273 CD4=2.3517705E-06
274 CD5=-2.0360899E-07
275 CD6=9.4187498E-09
276 CD7=-6.952056E-10
277 CD8=4.8360439E-12
278 CD9=-5.3232761E-14
279 CD10=3.2690826E-16
280 CD11=-8.757693E-19
281 GOTO 146
282 146 CONTINUE
283 CD0=1.7802618E01
284 CD1=1.2909006E00
285 CD2=1.9987808E-02
286 CD3=-6.787823E-04
287 CD4=6.8501186E-06
288 CD5=-4.124183E-08
289 CD6=1.3668450E-10
290 CD7=-1.9232534E-13
291 CD8=0.0
292 CD9=0.0
293 CD10=0.0
294 CD11=0.0
295 148 CONTINUE
296 CD1=CD0+CD1+CD2+CD3+CD4+CD5+CD6+CD7+CD8+CD9+CD10+CD11
297 148 CONTINUE
298 CD0=C01+CD2+CD3
299 IF(DSMH-3500)150,150,150
300 150 CONTINUE
301 150 CONTINUE
302 CD1=1.7866330E-01
303 CD2=-6.4582961E-03
304 CD3=-1.4694046E-03
305 CD4=1.9047721E-04
306 CD5=5.722092E-06
307 CD6=-2.6715335E-07
308 CD7=2.8929761E-08
309 CD8=-1.0573124E-09
310 CD9=2.1306976E-11
311 CD10=-2.6494492E-13
312 CD11=-4.3162531E-18
313 GOTO 156
314 152 CONTINUE
315 152 CONTINUE
316 CD2=1.8711536E03
C21 = -1.3477721E02  
C22 = 4.1114309E00  
C23 = -6.8902750E-02  
C24 = 6.8561083E-04  
C25 = -4.0530542E-06  
C26 = 1.3187613E-08  
C27 = -8.228129E-11  
C28 = 0.00000000000000  
C29 = 0.00000000000000  
C210 = 0.00000000000000  
C211 = 0.00000000000000  
C2A = C20 + C21 * CAS + C22 * CAS**2 + C23 * CAS**3 + C24 * CAS**4 + C25 * CAS**5  
C2B = C26 * CAS**6 + C27 * CAS**7 + C28 * CAS**8 + C29 * CAS**9  
C2C = C210 * CAS**10 + C211 * CAS**11  
C2 = 1000.0 * (C2A + C2B + C2C)  
CK0 = -7.8699233E-05  
CK1 = -3.2234471E-01  
CK2 = 1.4716139E00  
CK3 = -1.7693431E00  
CK4 = -9.5928956E-01  
CK5 = -1.3306691E-01  
CK6 = 2.3581299E-02  
CK7 = -2.7710716E-03  
CK8 = 2.1279022E-04  
CK9 = -1.02350109E-05  
CK10 = 2.7966863E-07  
CK11 = 3.3061349E-09  
GOTO 138  
CKAP1 = CK0 + CK1 * CAS + CK2 * CAS**2 + CK3 * CAS**3 + CK4 * CAS**4 + CK5 * CAS**5  
CKAP2 = CK6 * CAS**6 + CK7 * CAS**7 + CK8 * CAS**8 + CK9 * CAS**9 + CK10 * CAS**10  
CKAP3 = CK11 + CK12 + CK13  
CKAP = 3 * (CKAP1 + CKAP2 + CKAP3)  
CKAP = CKAP / 3.0  
E0 = 1.3051737  
C0B = 0.0069850  
EOA = 1.1234886
370- COA=0.0103823 00011830
371- FCT1=1.0 00011835
372- FCT2=1.0 00011840
373- FCT3=1.0 00011845
374- FCT4=1.0 00011850
375- FREQ=15.0 00011855
376- FREQT=15.0 00011860
377- FREQR=8.0 00011865
378- IF(OSM-3500,162,162 00011870
379- CONTINUE 00011875
380- BBFO=-5.2502975E-02 00011880
381- BBFI=2.4290747E-01 00011885
382- BBF2=-5.3572645E-02 00011890
383- BBF3=6.637522E-03 00011895
384- BBF4=-2.850117E-04 00011900
385- BBF5=4.2239845E-06 00011905
386- BBF6=8.6076538E-07 00011910
387- BBF7=-3.590619E-08 00011915
388- BBF8=7.7332822E-10 00011920
389- BBF9=-9.636165E-12 00011925
390- BBF10=6.2002737E-14 00011930
391- BBF11=-1.7094962E-16 00011935
392- GOTO 164 00011940
393- CONTINUE 00011945
394- BBFO=-1.6156112E02 00011950
395- BBFI=1.2157621E01 00011955
396- BBF2=-3.7074985E-01 00011960
397- BBF3=6.3966447E-03 00011965
398- BBF4=-6.3479565E-05 00011970
399- BBF5=7.107308E-07 00011975
400- BBF6=-1.1051895E-09 00011980
401- BBF7=1.5976850E-12 00011985
402- BBF8=0.0 00011990
403- BBF9=0.0 00011995
404- BBF10=0.0 00020000
405- BBF11=0.0 00020005
406- CONTINUE 00020010
407- BBFA=BBFO+BBF1+CAS+BBF2+CAS2+BBF3+CAS3+BBF4+CAS4 00020015
408- BBFB=BBF5+CAS5+BBF6+CAS6+BBF7+CAS7+BBF8+CAS8 00020200
409- BBFC=BBF9+CAS9+BBF10+CAS10+BBF11+CAS11 00020225
410- BBF=BBFA+BBFB+BBFC 00020230
411- IF(OSM-35001180,180,182 00020235
412- CONTINUE 00020240
413- EEF0=-1.6392956E-04 00020245
414- EEF1=3.8696358E-02 00020250
415- EEF2=-5.7549472E-03 00020255
416- EEF3=9.1075738E-04 00020260
417- EEF4=-7.1071983E-05 00020265
418- EEF5=3.6245638E-06 00020270
419- EEF6=-1.2056023E-07 00020275
420- EEF7=2.8953761E-09 00020280
421- EEF8=-4.470369E-11 00020285
422- EEF9=4.4053809E-13 00020290

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423* EEF10=2.4905921E-15
424* EEF11=6.1533305E-18
425* GOTO 189
426* CONTINUE
427* IF(DSMM<4000)184,184.184
428* GOTO 189
429* EEF0=2.9869271E04
430* EEF1=-1.9.805576E03
431* EEF2=5.2476916E01
432* EEF3=-6.9.4580127E-01
433* EEF4=4.5919943E-03
434* EEF5=-1.2131410E-05
435* EEF6=0.0
436* EEF7=0.0
437* EEF8=0.0
438* EEF9=0.0
439* EEF10=0.0
440* EEF11=0.0
441* GOTO 189
442* CONTINUE
443* EEF0=1.586114E02
444* EEF1=1.0529675E01
445* EEF2=2.9687507E-01
446* EEF3=-6.6.404242E-03
447* EEF4=-4.3351686E-05
448* EEF5=-2.4200222E-07
449* EEF6=-7.4825315E-10
450* EEF7=-9.8764537E-13
451* EEF8=0.0
452* EEF9=0.0
453* EEF10=0.0
454* EEF11=0.0
455* 189 CONTINUE
456* EEFIA=EEF0+EEF1+EEF2+EEF3+EEF4+EEF5+EEF6+EEF7+EEF8+EEF9+EEF10+EEF11
457* FS=16.0
458* PI=3.14159265
459* POI51=0.3
460* POI52=0.3
461* POI53=0.35
462* POI54=0.35
463* GMEGT=2.0*PI*FREQT
464* GMEGR=2.0*PI*FREQR
465* EMD1=1.3*10**4
466* EMD2=1.3*10**6
467* EMD3=4.6*10**4
468* EMD4=10000
469* GMD1=EMD/(2.0*(1.0+POI51))
470* GMD2=EMD/(2.0*(1.0+POI52))
471* GMD3=EMD/(2.0*(1.0+POI53))
00002360
00002365
00002370
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00002585
00002590
00002595
00002600
00002605
00002610
00002615
00002620
529  ZZ = 7.2*(C1**2)*(BB**2)*((SKO-VM*OMEG**2)**2) - ALPH2 00002625
530  ZZ = 2*(SKO-VM*OMEG**2) 00002630
531  ZZ = (C1**2)*(BB**2)/(2.0*C2*(SKO-VM*OMEG**2)) 00002635
532  ZZ = (ZZ/ZZ - VV) 00002640
533  ZZ = ABS (EE) 00002645
534  ZZ = SKO*C1 + BB*BF*ADYN**2 + C2*EE*EEF*ADYN**4 00002650
535  ZZ = STIF*SQRT((SK-VM*OMEG**2)**2 + (C0*OMEG**2)) 00002655
536  ZZ = PS/(PI*AO**2) 00002660
537  ZZ = POI5*POI1 00002665
538  ZZ = Q0*Q1 00002670
539  ZZ = SHEAR1 00002675
540  ZZ = DLO = PI*(AO*((1.0-POI5)**2)/(2.0*(1.0-2.0*POI5))) 00002680
541  ZZ = DLO = DLO = CC2 00002685
542  ZZ = IF(DLO-HI > 18.6.240 00002690
543  ZZ = FK00 = 2.0*PI*(AO**2)*Q1*SHEAR1/DLO 00002695
544  ZZ = FK00 = FK00*CC2 00002700
545  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002705
546  ZZ = FL2 = DLO**2/CC2 00002710
547  ZZ = FL4 = DLO*(DLO/DLO)**2 00002715
548  ZZ = FL4 = EL4 + EL4/CC2 00002720
549  ZZ = EL4 = EL4/CC2 00002725
550  ZZ = DL4 = CL4*EL4 00002730
551  ZZ = BBA = -4.0*PI*(AO**2)*Q1*SHEAR1*DL2/(DLO**2) 00002735
552  ZZ = BBA = BBA*CC2 00002740
553  ZZ = D12 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002745
554  ZZ = D12 = D12/CC2 00002750
555  ZZ = D14 = D14*CC2 00002755
556  ZZ = DLO = DLO = CC2*(S2*AO + AC1*(S1-S2)) + PI/2.0 00002760
557  ZZ = DLO = DLO = CC2*(S2*AO + AC1*(S1-S2)) + PI/2.0 00002765
558  ZZ = DLO = DLO = CC2*(S2*AO + AC1*(S1-S2)) + PI/2.0 00002770
559  ZZ = 7*FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002775
560  ZZ = FK00 = FK00*CC2 00002780
561  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002785
562  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002790
563  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002795
564  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002800
565  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002805
566  ZZ = FL2 = BB*(DLO**2)/(4.0*PI*(AO**2)*Q0*SHEAR) 00002810
567  ZZ = GG12 = Q1*SHEAR1 - Q2*SHEAR2 00002815
568  ZZ = GG12 = GG12*CC2 00002820
569  ZZ = GG12 = GG12*CC2 00002825
570  ZZ = GG12 = GG12*CC2 00002830
571  ZZ = GG12 = GG12*CC2 00002835
572  ZZ = EEA = 6.0*PI*(AO**2)*Q1*SHEAR1*DL2/(DLO**2) 00002840
573  ZZ = EEA = EEA*CC2 00002845
574  ZZ = GO220 00002850
575  ZZ = D10 = D10/CC2 00002855
576  ZZ = D10 = D10/CC2 00002860
577  ZZ = D10 = D10/CC2 00002865
578  ZZ = D10 = D10/CC2 00002870
579  ZZ = D10 = D10/CC2 00002875
580  ZZ = D10 = D10/CC2 00002880
581  ZZ = D10 = D10/CC2 00002885

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\begin{align*}
582 & \quad GL22 &= GL2 / 2.0 \\
583 & \quad DL2 &= BB \cdot (DL0 / 3) / (4.0 \cdot PI \cdot (AO^2) \cdot CC2 / GL2) \\
584 & \quad FL4 &= 3.0 \cdot (HL1 \cdot QA1 / HQ2 \cdot QQ23) + Q3 \cdot SHEAR3 \cdot DL0 \\
585 & \quad DL14 &= (DL2 \cdot MM^2) / (4.0 \cdot PI \cdot (CC2 \cdot AO^2) / GL2) \\
586 & \quad BB &= -4.0 \cdot PI \cdot (AO^2) \cdot DL2 / CC2 \cdot GL2 / DL0 / 3 \\
587 & \quad RH0 &= 3.0 \cdot ((DL2 / DL0) / 2) - 2.0 \cdot DL4 / DL0 \\
588 & \quad DELTA &= DL0 / DL0 / 2 - DL0 / DL0 \\
589 & \quad EEAI &= 6.0 \cdot PI \cdot (AO^2) / CC2 / DL0 / 2 \\
590 & \quad DELTA &= (DL2 / DL0) / 2 - DL0 / DL0 \\
591 & \quad EEAI &= 6.0 \cdot PI \cdot (AO^2) / CC2 / DL0 / 2 \\
592 & \quad DL0 &= -1.6182520E-01 \\
593 & \quad DL01 &= 2.9406204E01 \\
594 & \quad DL02 &= 1.5550641E01 \\
595 & \quad DL03 &= 1.1928522E01 \\
596 & \quad DL04 &= -4.5978025E00 \\
597 & \quad DL05 &= 8.5997394E-01 \\
598 & \quad DL06 &= -1.0403998E-01 \\ 
599 & \quad DL07 &= 6.323389E-03 \\
600 & \quad DL08 &= -3.5492892E-04 \\
601 & \quad DL09 &= 1.0179406E-05 \\
602 & \quad DL010 &= -1.6440288E-07 \\
603 & \quad DL011 &= 1.1439359E-09 \\
604 & \quad DL0A &= DL0 + DL01 \cdot CDS + DL02 \cdot CDS^2 + DL03 \cdot CDS^3 + DL04 \cdot CDS^4 \\
605 & \quad DL05 &= DL05 + DL06 \cdot CDS^4 + DL07 \cdot CDS^5 + DL08 \cdot CDS^6 \\
606 & \quad DL09 &= DL09 + DL010 \cdot CDS^7 + DL011 \cdot CDS^8 \\
607 & \quad DL00 &= 1000.0 \cdot (DL0A + DL0B + DL0C) \\
608 & \quad ALPP &= (CKAP - 1.0) / AO / DL0 \\
609 & \quad FAO &= 1.0 \cdot ALPP \cdot DL0 / AO + ((ALPP \cdot DL0 / AO)^2) / 3.0 \\
610 & \quad FAN1 &= 1.0 \cdot ALPP \cdot H1 / AO + ((ALPP \cdot H1 / AO)^2) / 3.0 \\
611 & \quad FAB2 &= H1 / H2 + H1 / H2 + H2 \cdot H2 / 2 \\
612 & \quad FAN2 &= 1.0 \cdot ALPP \cdot (H1 \cdot H2) / AO + ((ALPP \cdot AO)^2) / 2 \cdot FAB2 / 3.0 \\
613 & \quad FAB3 &= H2 \cdot H2 + H2 \cdot H2 + H2 \cdot H2 / 2 \\
614 & \quad FAB4 &= 1.0 \cdot ALPP \cdot (H2 \cdot H2) / AO + ((ALPP \cdot AO)^2) / 3 \cdot FAB3 / 3.0 \\
615 & \quad FAB5 &= H2 \cdot H2 \cdot H2 + H2 \cdot H2 + H2 \cdot H2 / 2 \\
616 & \quad FAB6 &= 1.0 \cdot ALPP \cdot (H3 \cdot H3) / AO + ((ALPP \cdot AO)^2) / 2 \cdot FAB4 / 3.0 \\
617 & \quad FAC1 &= FAN1 / FADO \\
618 & \quad FAC2 &= FAN2 / FADO \\
619 & \quad FAC3 &= FAN3 / FADO \\
620 & \quad FAC4 &= FAN4 / FADO \\
621 & \quad FAC5 &= FAN5 / FADO \\
622 & \quad FAC6 &= FAN6 / FADO \\
623 & \quad GQ1 &= 0.1 \cdot SHEAR1 \cdot Q4 \cdot SHEAR4 \\
624 & \quad GQ2 &= 0.2 \cdot SHEAR2 \cdot Q4 \cdot SHEAR4 \\
625 & \quad GQ3 &= 0.3 \cdot SHEAR3 \cdot Q4 \cdot SHEAR4 \\
626 & \quad FLO &= 2.0 \cdot PI \cdot (AO^2) / DL0 = 2 \\
627 & \quad FK0 &= 4.0 \cdot PI \cdot (AO^2) / CC2 \cdot GL2 \\
628 & \quad FLG2 &= 2.0 \cdot (HL1 \cdot QA1 / HQ2 \cdot QQ23) + FAC2 + H3 \cdot HQ34 \cdot FAC3 \\
629 & \quad GL2 &= GL2 \cdot QA4 \cdot SHEAR4 \cdot DL0 \cdot FAC4 \\
630 & \quad DL2 &= BB \cdot (DL0 / 3) / (4.0 \cdot PI \cdot (AO^2) / CC2 / GL2) \\
631 & \quad FL4 &= 3.0 \cdot (HL1 \cdot QA1 / HQ2 \cdot QQ23) + FAC2 + H3 \cdot HQ34 \cdot FAC3 \\
632 & \quad FL4 &= (FL4 \cdot QA4 \cdot SHEAR4 \cdot DL0 \cdot FAC4 \\
633 & \quad DL9 &= (DL2 / DL0 / EE / (DL0 / 3) / (4.0 \cdot PI \cdot (AO^2) / CC2 / GL2 / DL0 / 3) / GL2 \\

\end{align*}
635 RNO=3.0*(DL2/DLO)**2-2.0*DL4/DLO
636 DELTA=CDL2/DLO**2-DL4/DLO
637 EEAI=6.0*PI*(AO**2)*CC2/DLO**2
638 EEA2=EEAI+DELTA*Q4*SHEAR4*DLO*FAC4
639 EEA=EEAI*EEA2
640 ARG2=H1*EMOO1+H2*EMOD2+H3*EMOD3*(DLO-HH3)*EMOD4
641 CONTINUE
642 ZPCl)=-1.0*FS
643 ZP(2)=FKOO
644 ZP(3)=0.0
645 ZP(4)=BBA
646 ZP(5)=0.0
647 ZP(6)=EEA
648 CALLDOWN(ZP, 5, RRCR)
649 & SX,3N-FS,5X.1PE20.7/SX.4H4FKOO,4X.1PE20.7/SX.1PE20.7
650 & 5X.3HBA,5X.1PE20.7/15X.1PE20.7/3X.3HEA.5X.1PE20.71
651 XE<0.0
652 XE=RRCK)
653 CONTINUE
654 VMR=VM+BC2*SCO*( (BC1-FREQR)/OMEGR)**2
655 WR=VMR*AG/16.0
656 OMEG=OMEGR
657 RBA=4.0
658 REA=(1.0-CUR)*180.0-CUR*17.0
659 ETA=(4.0/3.0)*C1*EBF
660 SKOT=FKOO+3.0*RBA*BBA*(XE**2)+5.0*REA*EEA*(XE**4)
661 CCC=CO
662 SOT=SOT+(SKOT-VMR*OMEGE)**2+2*(CCC*OMEGE)**2
663 ST=SKOT+C1*BBA*BBF*(ADYN**2)+C2*EEA*EEF*(ADYN**4)
664 FDYN=FDYN
665 FPSIT=(FDYN**2)/SOT*4
666 ADYN=FPSIT+(1.0*ALPH1*FPSIT+ALPH2*FPSIT)**2
667 OMEGTR=SOT*SKOT/VMR
668 VMET=VM+BC2*SKOT*(BC1-FREQu)/OMEGTR**2
669 WET=VMET*AG/16.0
670 VMRT=VM+BC2*SKOT*(BC1-FREQ1)/OMEGTR**2

A-17
A-18
C CONTINUE
SKOD=F5/XEE-BB*(XEE**2)-EE*(XEE**4)
STOP
CONTINUE 00003665
SKOE=FS/XEE-BB*(XEE**2)-EE*(XEE**4) 00003670
STOP 00003680
GO TO 628 00003690
WRITE(6,45)
FORMAT('PROGRAM SIZE LIMIT IS 100 DATA POINTS.') 00003750
WRITE(6,46)
FORMAT('ELEVENTH DEGREE IS THE LIMIT.') 00003755
READ(FNAME,592)AO 00003765
N=5 00003775
READ(FNAME,593,END=602)X(I),Y(I) 00003785
X(I+1)=-X(I) 00003795
Y(I+1)=-Y(I) 00003800
CONTINUE 00003815
M=I-1 00003825
PRINT 617,ITEMP
FORMAT(/' TOO FEW POINTS FOR FITTING DEGREE',1') 00003855
STOP 00003860
END

SUBPROGRAM ZORP 00003840
THE SUBPROGRAM ZORP2 CALCULATES THE ROOTS OF THE FIFTH ORDER 00003850
POLYNOMIAL THAT CONNECTS THE STATIC LOAD AND THE STATIC 00003860
ELASTIC DISPLACEMENT OF THE PAVEMENT SURFACE DIRECTLY BENEATH 00003870
THE VIBRATOR BASEPLATE 00003875
ZORP2 00003880
Routines for solving polynomials 00003890
SUBROUTINE POLYNOMIAL(A,M,A,R,C,PR,PC,RHO,PHI) 00003885
DIMENSION A(9999) 00003890
IF(RHO)10,5,10 00003895
R=A(I) 0003900
C=0. 00003905
PR=A(2) 00003910
PC=0. 00003915
RETURN 00003920
V1=1. 00003925
V2=0. 00003930
R=A(1) 00003935
C=0. 00003940
PR=0. 00003945
PC=0. 00003950
WI=RHO*COS(PHI) 00003955
A-19
DO 20 I=2,NN
T1=M1*V1-W2*V2
V2=M2*V1+M1*V2
V1=T1
R=R+A(I)*V1
C=C+A(I)*V2
PR=PR+A(I)*(I-I)*V1
PC=PC+A(I)*(I-I)*V2
PR=PR/RHO
PC=PC/RHO
RETURN

SUBROUTINE ARCTA(X,Y,ANGLE)
PI=3.14159265
IF(X)10,30,20
ANGLE=ATAN(Y/X)+PI*SIGN(1.,Y)
RETURN
ANGLE=ATAN(Y/X)
RETURN
IF(Y)40,60,50
ANGLE=PI/2.
RETURN
ANGLE=PI/2.
RETURN
RETURN
END

SUBROUTINE DOHNN(A,NARRR,CR)
DIMENSION A(9999),RR(9999),CR(9999),Q(101),B(3)
J=0
N-NARR
NPLI=N+1
ANPP=A(NPLI)
DO 102 I=1,NPL1
IF (A(I))110,102,110
LU=LU+1
LL=LL+1
IF(C-2.**LU)100,101,100
IF(C-2.**LL)101,105,105
HAR=HAR+1
GO TO 5001
II=(LU+LL)/2
IF(C-2.***II)109,110,110,109
LL=II
GO TO 111
LU=II
IF(LU-LL-1)111,112,105
IB=IB+1
IF(IB)114,120,114
RETURN
}
847* DO 115 I=1,NPL1
848* II=I-1
849* A(I)=A(I)*((2.**II)**II)
850* DO 121 J=1,NPL1
851* A(J)=A(J)/A(NPL1)
852* IF(N<2001.2001,206
853* IF(A(J)>301,211,301
854* 211 J=J+1
855* RR(J)=0.
856* CR(J)=0.
857* DO 221 J=1,N
858* A(J)=A(J+1)
859* N=N-1
860* GO TO 201
861* 301 IF(N<23401.501,401
862* 401 CALL GRAD(A,N,X,Y)
863* 421 IF(ABS(Y)<ABS(X*1.E-6))431,441
864* 431 Y=0.
865* 441 J=J+1
866* RR(J)=X
867* CR(J)=Y
868* IF(Y<101.461
869* 461 J=J+1
870* RR(J)=X
871* CR(J)=Y
872* GO TO 1011
873* 501 DISC=A(2)**2-4.*A(1)
874* IF(DISC<1.541,541
875* 521 Y=SQRT(-DISC)/2.
876* 541 X=-A(2)/2.
877* GO TO 421
878* 561 J=J+1
879* RR(J)=(-A(2)*SQRT(DISC))/2.
880* CR(J)=0.
881* GO TO 1021
882* 601 J=J+1
883* RR(J)=-A(I)
884* CR(J)=0.
885* GO TO 2001
886* 1011 B(I)=X**2*Y**2
887* B(2)=2.*X
888* B(3)=1.
889* NB=2
890* GO TO 1041
891* IF(N<1081,1071,1081
892* 1071 N=N-1
893* 1081 CALL OIV(A,B,N,NB,Q)
894* 1061 J=J+1,N
895* 1041 CALL DIVA(A,M,NB,Q)
896* 1061 A(J)+Q(J)
897* 1071 N=N-1
898* 1081 GO TO 201
899* GO TO 201
GO TO 201


DO 2000 I=1,NAR

RR(I)=RR(I)*(2.+IB))

CR(I)=CR(I)*((1.+IB))

NP1=NAR+1

DO 2011 I=2,NP1

A(I)=0.

A(1)=1.

NA=0

J=1


B(3)=1.

B(2)=-2.*RR(J)

B(1)=RR(J)*2+CR(J)**2

J=J+2

GO TO 2081

NB=1

B(2)=1.

B(1)=-RR(J)

J=J+1

CALL MTALGD(ANABNBQ)

NA=NB-NA

NAPLI=NA+1

201 I=1,NAPLI

A(I)=Q(I)

IF(CNA-NAR) 3001.3001.

DO 3011 J=1,NPLI

A(J2)=A(J2)-ANPP

RETURN

END

SUBROUTINE GRADCA,N,XZ,YZ)

DIMENSION A(9999),XZ,YZ,PR(3),CP(3),RHO(3),PHI(3)

DIMENSION ABSP(3)

PI=3.14159265

MST=1

101 XZ=0.0

YZ=1.0

102 DZ=2.

RHOZ=1.

PHIZ=PI/2.

CALL POLY(N,A,RZ,CZ,PR,CZ,RHOZ,PHIZ)

SU=SQRT(PRZ**2+PCZ**2)

ABSPZ=SQRT(RZ**2+CZ**2)

U-Z.*ABSPZ*SU

PSI=ATAN(U)

TDP=2.*PCZ*CZ

B0T-((RZ*PRZ+CZ*PCZ)

CALL ARCTA(BOT,TOP,THETA)

COSI=COS(THETA*PHIZ)

SINE=SIN(THETA*PHIZ)
953* IF(ABSPZ)300,500,300
954* 300 IF(SU)301.500,301
955* 301 IF(RHOZ)321.401,321
956* 321 IF(ABSPZ/(RHOZ*SU)-1.E-7)5001,5001,701
957* 351 IF(ABSPZ/(RHOZ*SU)-10.**(-MTST))801,801,401
958* 401 DZ=DZ/8.0
959* IM=0
960* DO 431 I=1,3
961* DZ=DZ**2
962* X(I)=XZ+DZ*COS(I)
963* Y(I)=YZ+DZ*SINE
964* RHO(I)=SQRT(X(I)**2+Y(I)**2)
965* CALL ARCTA(X(I), Y(I), PH(S(I)))
966* CALL POLY(N,A,CP(I),PH(I),PC(I),RHO(I),PH(I))
967* ABSP(I)=ABS(P(I)**2)
968* IF(ABSP-ABSP(I))431,431,401
969* 421 ABSPZ=ABSP(I)
970* IM=I
971* 431 CONTINUE
972* IF(IM) 441,441,461
973* 441 DZ=DZ/8.0
974* IF(RHOZ)443,445,443
975* 443 IF(DZ/RHOZ-1.E-7)451,451,401
976* 445 IF(DZ-1.E-7)451,451,401
977* 451 IF(SU-ABS(PZ)) 501,501,5001
978* 461 DZ=(2.**IM-2)**DZ
979* X(Z=X(I))
980* 980 YZ=Y(I)
981* PHIZ=PH(S(I))
982* PRZ=PR(S(I))
983* PCZ=PC(S(I))
984* RHOZ=RHO(S(I))
985* RZ=RZ(S)
986* CZ=CP(S(I))
987* GO TO 221
988* 501 DZ=1.0
989* 510 DTHTA=PT/10.
990* 521 THETA=0.0
991* DO 561 I=1,20
992* THETA=THETA+DTHTA
993* X5=XZ+DZ*COS(PHIZ-THETA)
994* Y5=YZ+DZ*SINE(PHIZ-THETA)
995* RHOS=SQRT(X5**2+Y5**2)
996* CALL ARCTA(XS,Y5,PW(S))
997* CALL POLY(N,A,CP(S),PCS,RHOS,PW(S))
998* ABSP(I)=ABS(P(S)**2)
999* IF(ABSPZ-ABSP(I)) 561,561,601
1000* 561 CONTINUE
1001* DO 561 I=1,20
1002* DZ=DZ/2.
1003* IF(RHOS)563,565,563
1004* 563 IF(DZ/RHOS-1.E-7)5001,5001,521
1005* 565 IF(DZ-1.E-7)75001,5001,521
1006* 601 XZ=X5

A-23
1006# YZ=YS 00005020
1007# PHZ=PHIS 00005025
1008# RH0Z=RH0S 00005030
1009# ABSZ=ABSP(1) 00005035
1010# PRZ=PRS 00005040
1011# PCZ=PCS 00005045
1012# RZ=RS 00005050
1013# CZ=CS 00005055
1014# GO TO 221 00005060
1015# 701 IF(PSI-1.E-6)711.711,351 00005065
1016# 711 IF(SU-ABSPZ)501,501.351 00005070
1017# 801 RHO(1)*RHOZ*BOT/SU**2 00005075
1018# IF(RHO(1))901,901.816 00005080
1019# 816 PHI(1)=PHIZ+TOP/(RHOZ*SU**2) 00005085
1020# 821 CALL POLY(NA,RZ,CZ,PRZ.PCZ,RHO(1),PHI(1)) 00005090
1021# ABSZ=SQRT(RZ**2+CZ**2) 00005095
1022# IF(ABS(1)-ABSPZ)851,881 00005100
1023# 841 XZ=RHOZ*COS(PHIZ) 00005105
1024# YZ=RHOZ*SIN(PHIZ) 00005110
1025# GO TO 5001 00005115
1026# 851 RHOZ=RHOC(1) 00005120
1027# ABSPZ=ABSP(1) 00005125
1028# PHIZ=PHI(1) 00005130
1029# TOP=RZ*PCZ-CZ*PRZ 00005135
1030# BOT=-(RZ*PRZ+CZ*PCZ) 00005140
1031# SU=SQRT(PRZ**2+PCZ**2) 00005145
1032# IF(SU)855,501,855 00005150
1033# 855 U2=ABSZ*SU 00005155
1034# PSI=ATAN(U) 00005160
1035# IF(SU<1.E-6)651,61,61 00005165
1036# 651 IF(SU<1.E-7)641,641 00005170
1037# 641 IF(SU<1.E-7)631,631 00005175
1038# 631 IF(SU<1.E-7)621,621 00005180
1039# 621 IF(SU<1.E-7)611,611 00005185
1040# 611 IF(SU<1.E-7)601,601 00005190
1041# 601 IF(SU<1.E-7)591,591 00005195
1042# 591 IF(SU<1.E-7)581,581 00005200
1043# 581 IF(SU<1.E-7)571,571 00005205
1044# 571 IF(SU<1.E-7)561,561 00005210
1045# 561 IF(SU<1.E-7)551,551 00005215
1046# 551 IF(SU<1.E-7)541,541 00005220
1047# 541 IF(SU<1.E-7)531,531 00005225
1048# 531 IF(SU<1.E-7)521,521 00005230
1049# 521 IF(SU<1.E-7)511,511 00005235
1050# 511 IF(SU<1.E-7)501,501 00005240
1051# 501 IF(SU<1.E-7)491,491 00005245
1052# 491 IF(SU<1.E-7)481,481 00005250
1053# 481 IF(SU<1.E-7)471,471 00005255
1054# 471 IF(SU<1.E-7)461,461 00005260
1055# 461 IF(SU<1.E-7)451,451 00005265
1056# 451 IF(SU<1.E-7)441,441 00005270
1057# 441 IF(SU<1.E-7)431,431 00005275
1058# IF(SU<1.E-7)61,61,61 00005280

A-24
1059*  N2=J1-J2+1
1060*  IF(N2-NBPL.171,71,81)
1061*  TEMP=TEMP+A(J2)*B(N2)
1062*  CONTINUE
1063*  C(J1)=TEMP
1064*  CONTINUE
1065*  RETURN
1066*  END
1067*  SUBROUTINE DIV(A,B,NA,NB,Q)
1068*  DIMENSION A(9999),B(9999),Q(9999)
1069*  K=NA-NB+1
1070*  DO 61 J1=1,11
1071*  Q(J1)=0.
1072*  DO 101 JK=1,HS
1073*  DO 201 I=1,NA-NB+1
1074*  TEMP=0.
1075*  IF(K=1)61,621,621
1076*  DO 62 JJ=1,K
1077*  J=JJ-1
1078*  IF(J<=NB-K)11,121,121
1079*  IF(J<=K)11,121,121
1080*  Q(J)=A(NB-K-J)
1081*  61  DO 201 I=1,NA-NB+1
1082*  201  I=I2+I11
1083*  211  DO 291 JJ=1,K
1084*  291  CONTINUE
1085*  301  I=I2+NA-K
1086*  391  Q(J)=A(NB-K)-TEMP
1087*  5001  RETURN
1088*  END
1089*  START  ACNM=FTD5FO01
1090*  7000
1091*  2  1.2
1092*  4  2.5
1093*  6  3.85
1094*  8  5.5
1095*  10  7.5
1096*  12  9.4
1097*  14  11.5
1098*  STOP
1099*  EOJ
The computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness for rigid and flexible pavements in terms of the value of the subgrade modulus that is determined from results of vibratory nondestructive testing and in terms of the elastic moduli of the pavement layers.

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DOCUMENTATION OF THE COMPUTER PROGRAM PAVEVAL

PROGRAM IDENTIFICATION

a. Program Title. WES Pavement Evaluation Program

b. Program Code Name. PAVEVAL

c. Writer. Richard A. Weiss and Ricky Austin

d. Organization. U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180

e. Date. July 1977

f. Source Language. Fortran IV

Abstract. Program calculates the allowable load-carrying capacity and required overlay thickness of rigid and flexible pavements for single-, dual-, and dual-tandem gear configurations.
ENGINEERING DOCUMENTATION

Narrative Description. The allowable load-carrying capacity and required overlay thickness of a pavement is calculated by the combined methods of vibratory nondestructive testing and layered elastic theory. For flexible pavements, a limiting vertical strain in the subgrade and a limiting tensile strain in the AC layer are used, while for rigid pavements, a limiting tensile stress at the bottom of the PCC layer is used to relate the allowable load-carrying capacity and the required overlay thickness to the pavement structure. The computer program PAVEVAL is used to implement the layered elastic theory method of pavement evaluation. This computer program is also used to calculate the allowable load-carrying capacity and the required overlay thickness of rigid and flexible pavements for single-wheel, dual-wheel, and dual-tandem-wheel loadings.

Method of Solution. For the calculation of the allowable load-carrying capacity, the computer program PAVEVAL iterates the wheel load until the operating stress and strain in the pavement are equal to a specified limiting value. For the calculation of the required overlay thickness, PAVEVAL iterates the overlay thickness until the operating stress and strain in the pavement are less than specified limiting values.

Program Capabilities. Three subroutines are used to calculate the limiting values of the stress and the strain in the pavement. An index called EKEY is used to select the type of limiting stress or strain condition that is to be used and the depth in the pavement at which the limiting stress or strain condition is applied.

Two subgrade subroutines of the program can be used to calculate the allowable load-carrying capacity and the required overlay thickness for flexible pavements. These subroutines express the limiting strain at the top of the subgrade in terms of the load repetitions and the value of the subgrade Young's modulus. The subroutine RNN gives the limiting strain at the top of the subgrade in terms of the total number of load repetitions and does not involve values of the subgrade Young's
modulus. A more accurate representation of the limiting vertical strain at the top of the subgrade is expressed in terms of the subgrade Young's modulus value and in terms of the yearly load repetition rate. This is done in subroutine FLEX. For AC pavements using subroutine FLEX, the values of the subgrade modulus are restricted to $500 < E_s < 30000$ psi. The computer program PAVEVAL automatically introduces the limiting tensile strain at the bottom of the AC layer.

For rigid pavements, the subroutine RPAL is used to describe the limiting value of the tensile stress at the bottom of the PCC layer. The limiting tensile stress is expressed in terms of the flexural strength ($R$), yearly load repetition number ($Y_m$), and the pass-to-coverage ratio for each type of landing gear.

The computer program PAVEVAL can calculate the allowable load for a rigid or a flexible pavement and the required overlay thickness for a rigid or a flexible pavement. An index EKEY2 is used to select these possibilities. By selecting the proper choices of EKEY and EKEY2, the allowable load and the required overlay thickness for rigid and flexible pavements can be calculated for a number of specified limiting stress and strain conditions.

**Printed Output.** The printed output consists of the allowable load-carrying capacity or the required overlay thickness for a pavement. The vertical strain at the top of the subgrade and the tensile strain at the bottom of the AC layer of flexible pavements, as well as the tensile stress at the bottom of the PCC layer, are also printed out. In addition, all components of the stress and the strain at points on the layer interfaces in the pavement directly under each of the wheel positions are printed out.

**Computer Equipment.** The program PAVEVAL was developed on the IBM 360/65 computer.
The input data instructions for this WES-600 CARDIN program are shown below. The meaning of these terms is explained in the following pages.

Line 1 (a) TEXT
Line 2 (b) NSYS
Line 3 (c) EKEY, EKEY2
Line 4 (d) AA, BB, RN, ALOAD, ALIN, CAREA, DSM, SWL
   or
   (d) ES, EA, YRN, ALOAD, ALIN, CAREA, DSM, SWL, PCRATIO
   or
   (d) DSM, FAC, YRN, R, ALOAD, ALIN, CAREA, SWL
   or
   (d) AA, BB, RN, ATHICK, ATLIN, CAREA, DSM, SWL
   or
   (d) ES, EA, YRN, ATHICK, ATLIN, CAREA, DSM, SWL, PCRATIO
   or
   (d) DSM, FAC, YRN, R, ATHICK, ATLIN, CAREA, SWL
Line 5 (e) NLAYS ISMO IRED
Line 6 (f) E(1), NU(1), THICK(1), AK(1) or ALK(1)
Line 7 (f) E(2), NU(2), THICK(2), AK(2) or ALK(2)
Line 8 (g) E(NLAYS), NU(NLAYS)
Line 9 (h) NLOAD
Line 10 (i) LDSTRS(1), RADIUS(1), X(1), Y(1), HOSTR(1), PSI(1)
Line 11 (i) LDSTRS(NLOAD), RADIUS(NLOAD), X(NLOAD), Y(NLOAD),
   HOSTR(NLOAD), PSI(NLOAD)
Line 12 (j) NPOS
Line 13 (k) LAYER(1), AX(1), AX(1), DEPTH(1), ETA(1)
Line 14 (k) LAYER(NPOS), AX(NPOS), AX(NPOS), DEPTH(NPOS), ETA(NPOS)
Line 15 If another problem is desired, return to line 3 and repeat process.

The meaning and example of each card type are as follows:

B-4
Card type (a) TEXT = problem identification, maximum of 80 characters.
Example line: Line No. Identifying information

Card type (b) NSYS = number of problems to run
Example line: Line No. NSYS

Card type (c) EKEY = limiting strain and stress subroutine code
1 = calls subroutine RNN
2 = calls subroutine FLEX
3 = calls subroutine RPAL
EKEY2 = pavement problem code
0 = allowable load
1 = overlay over flexible pavement
2 = overlay over rigid pavement
Example line: Line No. EKEY EKEY2

Card type (d) if EKEY = 1, EKEY2 = 0
AA = -0.1616727
BB = -2.2150779
RN = total number of load repetitions
ALOAD = initial load, lb
ALIN = load increment, lb
CAREA = contact area (\(\pi r^2\)), in.\(^2\)
DSM = dynamic stiffness modulus, for reference
SWL = 0
Example line: Line No. AA BB RN ALOAD ALIN CAREA DSM SWL

Card type (d) if EKEY = 2, EKEY2 = 0
ES = subgrade modulus, psi
EA = asphalt modulus of existing layer
YRN = yearly load repetition number
ALOAD = initial load, lb
ALIN = load increment, lb
CAREA = contact area (\(\pi r^2\)), in.\(^2\)
DSM = dynamic stiffness modulus, for reference
SWL = 0
PCRATIO = pass-to-coverage ratio

Example line: Line No. ES EA YRN ALOAD ALIN CAREA DSM SWL PCRATIO

Card type (d) if EKEY = 3, EKEY2 = 0
DSM = dynamic stiffness modulus, for reference
FAC = pass-to-coverage ratio
YRN = yearly load repetition number
R = flexural strength, psi
ALOAD = initial load, lb
ALIN = load increment, lb
CAREA = contact area ($\pi r^2$), in.$^2$
SWL = 0

Example line: Line No. DSM FAC YRN R ALOAD ALIN CAREA SWL

Card type (d) if EKEY = 1, EKEY2 = 1
AA = -0.1616727
BB = -2.2150779
RN = total number of load repetitions
ATHICK = initial thickness, in.
ATLIN = thickness increment, in.
CAREA = contact area ($\pi r^2$), in.$^2$
DSM = dynamic stiffness modulus, for reference
SWL = load on one wheel, lb

Example line: Line No. AA BB RN ATHICK ATLIN CAREA DSM SWL

Card type (d) if EKEY = 2, EKEY2 = 1
ES = subgrade modulus, psi
EA = asphalt modulus of existing layer, psi
YRN = yearly load repetition number
ATHICK = initial thickness, in.
ATLIN = thickness increment, in.
CAREA = contact area ($\pi r^2$), in.$^2$
DSM = dynamic stiffness modulus, for reference
SWL = load on one wheel, lb
PCRATIO = pass-to-coverage ratio

Example line: Line No. ES EA YRN ATHICK ATLIN CAREA DSM SWL PCRATIO

Card type (d) if EKEY = 3, EKEY2 = 2

DSM = dynamic stiffness modulus, for reference
FAC = pass-to-coverage ratio
YRN = yearly load repetition number
R = flexural strength, psi
ATHICK = initial thickness, in.
ATLIN = thickness increment, in.
CAREA = contact area \((\pi r^2)\), in.\(^2\)
SWL = load on one wheel, lb, for reference

Example line: Line No. DSM FAC YRN R ATHICK ATLIN CAREA SWL

Note for card type (e) and (f)
if, EKEY = 1, 2

ISMO = 0
IRED = 0
all AK(i)'s = 0

if, EKEY = 3, EKEY2 = 0

ISMO = 1
IRED = 1
AK(1) = 1000
other AK(i)'s = 0

if, EKEY = 3, EKEY2 = 1

ISMO = 1
IRED = 1
AK(1) = 0
AK(2) = 1000
other AK(i)'s = 0
Card type (e) NLAYS = number of layers in pavement system
\( ISMO^* = 0 \), request for rough computational procedure
\( IRED = 0 \), \( AK(i) \) is input in card type (f)
\( 1 \), request for smooth computational procedure
\( 1 \), \( ALK(i) \) is input in card type (f)

Example line: Line No. NLAYS ISMO IRED

* The smooth calculation procedure is more stable but less efficient than the rough procedure and is read for systems with frictionless slip between the layers or for cases when numerical instabilities are expected.

Card type (f) \( E(i) \) = modulus of layer \( i \)
\( NU(i) \) = Poisson's ratio of layer \( i \)
\( THICK(i)^* \) = thickness of layer \( i \)
\( AK(i)^{**} \) = interface compliance

or \( ALK(i) \) = reduced interface compliance

Example line: Line No. \( E(i) \) \( NU(i) \) \( THICK(i) \) \( AK(i) \) or \( ALK(i) \)

* When coding an EKEY2 = 1 or 2 problem, set \( THICK(1) = 1 \), and layer 1 is the overlay layer.

** \( AK(i) \) values are generally very small; thus, it may be more desirable to use \( ALK(i) \) where \( ALK(i) = \frac{E_i}{1 + V_i} \cdot AK(i) \). For complete adhesion between layers \( i \) and \( i + 1 \), set \( AK(i) = ALK(i) = 0 \). For almost frictionless slip between layers, set \( \frac{E_i}{1 + V_i} \cdot ALK(i) > 1000 \).

Card type (g) \( E(NLAYS) \) = modulus of last layer
\( NU(NLAYS) \) = Poisson's ratio of last layer

Example line: Line No. \( E(NLAYS) \) \( NU(NLAYS) \)

Card type (h) NLOAD\(^*\) = number of loaded areas
Example line: Line No. NLOAD

* Single wheel enter 1, dual wheel enter 2, dual-tandem enter 4
Card type (i) Load information: one card for each load

LDSTRS(i) = vertical load in units of load for loaded area i
RADIUS(i) = radius of loaded area i
X(i)* = abscissa of center of loaded area
Y(i)* = ordinate of center of loaded area
HOSTR(i) = horizontal load in units of load for loaded area i (normally zero)
PSI(i) = angle of HOSTR(i) with respect to positive X-axis in degrees (normally zero)

Example line: Line No. LDSTRS(i) RADIUS(i) X(i) Y(i) HOSTR(i) PSI(i)
*X(i) and Y(i) should always be zero.

Card type (j) NPOS = number of depths that will be used for iteration purposes
1, rigid pavement (EKEY = 3)
2, flexible pavement (EKEY = 1 or 2)

Example line: Line No. NPOS

Card type (k) LAYER(i)* = layer number for position i
AX(i) = abscissa of position (always zero)
AY(i) = ordinate of position (always zero)
DEPTH(i)* = depth from pavement surface to position
ETA(i) = angle from which position is observed with respect to the difference of the tangential loading (always zero)

Example line: Line No. LAYER(i) AX(i) AY(i) DEPTH(i) ETA(i)
*if, EKEY = 3, EKEY2 = 0
  LAYER(1) = 1
  DEPTH(1) = THICK(1)
if, EKEY = 3, EKEY2 = 2
  LAYER(1) = 2
  DEPTH(1) = THICK(1) + THICK(2), when THICK(1) = 1
if, \( EKEY = 1,2, EKEY2 = 0 \)

\[
\begin{align*}
LAYER(1) &= 1 \\
LAYER(2) &= \text{last layer (NLAYS)} \\
DEPTH(1) &= \text{THICK}(1) \\
\text{DEPTH}(2)^* &= \text{distance from pavement surface to top of subgrade}
\end{align*}
\]

if, \( EKEY = 1,2, EKEY2 = 1 \)

\[
\begin{align*}
LAYER(1) &= 2 \\
LAYER(2) &= \text{last layer (NLAYS)} \\
\text{DEPTH}(1) &= \text{THICK}(1) + \text{THICK}(2), \text{ where } \text{THICK}(1) = 1 \\
\text{DEPTH}(2)^* &= \text{distance from pavement surface to top of subgrade}
\end{align*}
\]

\[
\text{DEPTH}(2)^* = \sum_{i=1}^{(NLAYS-1)} \text{THICK}(i)
\]

PROGRAM LISTING

Data are coded, then typed into a disc file, and saved for later execution. The following listing is the sample problem with control cards.
COMPUTATION OF STRESSES, STRAINS AND DISPLACEMENTS

THIS PROGRAM CALCULATES THE FOLLOWING

1) RADIAL DISPLACEMENT
2) TANGENTIAL DISPLACEMENT
3) VERTICAL DISPLACEMENT
4) RADIAL STRESS
5) TANGENTIAL STRESS
6) VERTICAL STRESS
7) RADIAL AND TANGENTIAL STRESS
8) RADIAL AND VERTICAL STRESS
9) TANGENTIAL AND VERTICAL STRESS
10) RADIAL STRAIN
11) TANGENTIAL STRAIN
12) VERTICAL STRAIN
13) RADIAL AND TANGENTIAL STRAIN
14) RADIAL AND VERTICAL STRAIN
15) TANGENTIAL AND VERTICAL STRAIN

MASTERPROGRAM

PURPOSE

THIS MASTERPROGRAM READS DATA WHICH DETERMINE THE PHYSICAL BEHAVIOUR OF THE SYSTEM OF LAYERS AND WHICH DESCRIBE THE CONFIGURATION OF THE LOADS. FOR EACH SYSTEM THE REQUIRED STRESSES AND STRAINS AND DISPLACEMENTS ARE READ IN. THEN THE COORDINATES OF EACH POSITION ARE READ. FOR A COMPLETE INPUT-DESCRIPTION SEE GROUP EXTERNAL REPORT AMSR. SYSTEM DATA ARE OUTPUTTED BY

1) SYSTEM
2) MACONI
3) MA2CON
4) MACONI
5) CONPNT
6) ASYMP
7) GENDAT
8) INGRL
9) GENDAT
10) OUTPUT
11) JACOBI
12) ESORT

THE STRESSES, STRAINS AND DISPLACEMENTS ARE CALCULATED AND AFTER SUBSEQUENT CALLING IN OF

00010360
00010350
00010340
00010330
00010320
00010310
00010300
00010290
00010280
00010270
00010260
00010250
00010240
00010230
00010220
00010210
00010200
00010190
00010180
00010170
00010160
00010150
00010140
00010130
00010120
00010110
00010100
00010090
00010080
00010070
00010060
00010050
00010040
00010030
00010020
00010010
00010000
MAIN OUTPUTS OR HAS ALREADY OUTPUTTED

- ALL STRESSES, STRAINS AND DISPLACEMENTS.

- INDUCED BY EACH LOAD SEPARATELY AND EXPRESSED IN CYLINDRICAL COMPONENTS.

- ALL TOTAL STRESSES STRAINS AND DISPLACEMENTS EXPRESSED IN CARTESIAN COMPONENTS.

- ALL PRINCIPAL TOTAL STRESSES AND STRAINS, WITH THEIR PRINCIPLE DIRECTIONS.

- ALL MAXIMUM TOTAL SHEAR STRESSES AND STRAINS, WITH THEIR PRINCIPLE DIRECTIONS.

- THE MIDDPOINTS OF THE THREE ACOMPANYING MOHR'S CIRCLES.

- THE TOTAL STRAIN ENERGY AND STRAIN ENERGY OF DISTORTION.

THIS PROGRAM WAS MODIFIED TO SOLVE RIGID AND FLEXIBLE PAVEMENT PROBLEMS USING THE COMBINED METHODS OF THE BISAR PROGRAM AND VIBRATORY NONDESTRUCTIVE TESTING. THIS PROGRAM SOLVES OVERLAY THICKNESS AND ALLOWABLE LOAD PROBLEMS FOR EACH PAVEMENT TYPE.

PROGRAM NAME: PAVEVAL

CODED BY: RICKY AUSTIN, GEOTECHNICAL LABORATORY, WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

COMPUTER: WATERWAYS EXPERIMENT STATION, GE600

LANGUAGE: FORTRAN IV

DATE COMPLETED: SEPTEMBER 1978

SPECIAL REQUIREMENTS: CARDIN, REMOTE BATCH PROCESSING

STORAGE: DISC

LOGICAL STRESSEPSRLOMAID(27),NLN2,L2,NZEPNZEQ

INTEGER REQEST(27),IQ(3),DATE(3),ISTRSS(27),INTV(10),IVERI(7),IVER2(10)

REAL NU,K5,MU,LDSTRS(IO),HOSTR(10),LOAD,INTC17),V(15),X(IO),Y(10),A(3,3),HH(3,3),W(3),C(39],B(3,3),TEXT(15),ACCUR(3),PSI(10),AK(9),ALK(9)

DOUBLE PRECISION CZ,ELLE,ELLK

COMMON/ASDT/LAYER,NLAYS,M,R,Z,NU(10),ACCUR,LOADHOSTRSNZEROS,H(9)

COMMON/STRDTA/STRESS(27),EPS(17),RLOWST,CT,L,ACC

COMMON/CONST/CZ,ELLE,ELLK,ALMBDA

COMMON/CNTING/FIOMI,FIOO,FIO1,F1IM2,FIM,FIIO,F1I1

COMMON/TAPE/NOUT

COMMON/VSTR,STRL,ITER,STRL2

COMMON/RADIAL/STSL,DSM,F5,SNL

DIMENSION XTEMP(100),YTEMP(100),LAY(100),AXX(100)

B-12
DIMENSION AYY(100),DEP(100),ETAA(100)

INTEGER EKEY,EKEY2

DATA NBLANK,ISTRSSI,REFI,IREF2/

+,'ETT','EZZ','ERT','ETZ','UX','UY','SXZ','SXY','SZZ','SYY'00011060

+,'ETT','EZZ','ERT','ETZ','UX','UY','SXZ','SXY','SZZ','SYY'00011070

DATA REQEST/'UR','UZ','SRR','TT','SZZ','SRT','SRZ','STZ',00011080

+,'ETT','EZZ','ERT','ETZ','UX','UY','SXZ','SXY','SZZ','SYY'00011100

+,'ETT','EZZ','ERT','ETZ','UX','UY','SXZ','SXY','SZZ','SYY'00011110

DATA IVER1,IVER2/1,2,3,6,7,13,14,4,5,8,9,10,11,12,15,16,17/

DATA IDENT/'LOAD'/

C THESE ARE THREE ACC JACIES
ACCUR(1) IS USED FOR TESTING SEVERAL
VARIABLES AGAINST EACH OTHER.
ACCUR(2) IS USED FOR ABSOLUTE ACCURACY
OF THE INTEGRATION PROCEDURE
ACCUR(3) IS USED FOR RELATIVE ACCURACY
OF THE INTEGRATION PROCEDURE
NIN, NOUT ARE SYMBOLIC NAMES FOR INPUT AND
OUTPUT MEDIA RESP.

ACCUR(1)=1.0E-04
ACCUR(2)=1.0E-04
ACCUR(3)=1.0E-03
NIN=S
NOUT=6
VZ=1.414214
ITER = 0, INPUT NOT COMPLETE.
ITER = 1, INPUT COMPLETE.
ISKIP = 0, ITERATION NOT COMPLETE.
ISKIP = 1, ITERATION COMPLETE.
WRITE(NOUT,9000)

READ TEXT AND DATE CARD

READ(NIN,9010)TEXT
WRITE(NOUT,9020)TEXT

READ NUMBER OF SYSTEMS AND SET LOOP

CALL NFRD(NIN,NSYS,1)
CALL NFRD(NIN,EKEY,1)
CALL NFRD(NIN,EKEY,2)

B-13
GO TO (501, 502, 503), EKEY
CALL RNCl(AA, BB, RN, ALOAD, ALIN, CAREA)
GO TO 510
CALL FLEXES, EA, ALOAD, ALIN, CAREA, XS, AS, BS, YRN, PRATIO
GO TO 510
CALL RPAL(ALOAD, ALIN, CAREA)
CONTINUE
IF (EKEY2.GT.0) GO TO 520
IF (EKEY.LT.3) WRITE (NOUT, 900) STRL, STRL2, ALOAD, ALIN
IF (EKEY.EQ.3) WRITE (NOUT, 901) FS, DSM, ALOAD, ALIN, STSL
GO TO 550
WRITE (NOUT, 902) DSM, SWL, ATHICK, ATLIN
WRITE (NOUT, 903) DSM, SWL, FS, ATHICK, ATLIN
CONTINUE
READ NUMBER OF LAYERS AND THEIR PARAMETERS
CALL NFRD (N.JN, NLAYS, I)
CALL NFRD (NIN, ISMO, 2)
CALL NFRD (NIN, IRED, 2)
IF (NLAYS.EQ.1) GO TO 10
M = NLAYS - 1
DO 315 I = 1, M
CALL FFRD (NIN, E(C), I)
CALL FFRD (NIN, NU(I), 2)
CALL FFRD (NIN, THICK(I), 2)
CALL FFRD (NIN, AK(I), 2)
10 CALL FFRD (NIN, E(NLAYS), I)
C ---------------------------------------
C READ NUMBER OF LOADS AND THEIR PARAMETERS
CALL NFRD (NIN, NLOAD, 1)
NZEP = .FALSE.
NZEQ = .FALSE.
DO 30 I = 1, NLOAD
CALL FFRD (NIN, LDSTRS(I), 1)
CALL FFRD (NIN, RADIUS(I), 2)
CALL FFRD (NIN, Y(I), 2)
CALL FFRD (NIN, HOSTR(I), 2)
CALL FFRD (NIN, PSI(I), 2)
IF (EKEY2.GT.0) GO TO 560
LDSTRS(I) = ALOAD
CONTINUE
PSI(I) = .0174533 * PSI(I)
IF(LDSTRS(I).GT.ACCUR(1)) NZEP = .TRUE.
IF(HOSTR(I).GT.ACCUR(1)) NZEQ = .TRUE.
IF(IDENT.EQ.IREF2) WRITE(NOUT,9040) LDSTRS(I),HOSTR(I)
GO TO 30
LDSTRS(I) = LDSTRS(I)/(3.14159*RADIUS(I)*RADIUS(I))
HOSTR(I) = HOSTR(I)/(3.14159*RADIUS(I)*RADIUS(I))
CONTINUE

C TEST ON OBVIOUS MISTAKES IN SYSTEM'S DATA-CARDS.
C WHEN IRED > 0 THE REDUCED SPRINGCONST LIAN-
C WAS READ.
A NON-VANISHING SLIPRESISTANCE IS SUBSTITUTED TO PREVENT RIGID-BODY MOTION OF THE TOPLAYERS

DO 50 J = 1,NLAYS
IF((1.0-NU(J)).LT.ACCUR(1)) GO TO 410
IF(E(J).LT.ACCUR(1)) GO TO 420
IF(IRED.EQ.0) GO TO 40
ALK(J) = AK(J)*E(J)/(1.0+NU(J))
IF(ALK(J).LT.1000.0.OR..NOT.NZEQ) GO TO 50
ALK(J) = 1000.0
IF(ALK(J).LT.1000.0) GO TO 50
ALK(J) = ALK(J)/(1.0+NU(J))/E(J)
CONTINUE

CALL SYSTEM(ISYS,E,NU,THICK,AK,NLAYS,M,NLOAD,LDSTRS,HOSTR,ALK,RADIUS,X,Y,PSI,ISMO,IRED)
IF(.NOT.NZEP.AND..NOT.NZEQ) GO TO 430
CALL MACONI(ISMO,ALK,NEWSYS)
IF(NEWSYS.EQ.0) GO TO 70
CALL SYSTEM(ISYS,ENU,THICK,AK,NLAYS,M,NLOAD,LDSTRS,HOSTR,ALK,RADIUS,X,Y,PSI,ISMO,IRED)
READ STRESSES,STRAINS AND DISPLACEMENTS TO BE CALCULATED.
CONTINUE
DO 90 I=1,27
If REQUEST(I).EQ.NBLANK) GO TO 80
AID(I) = .TRUE.
GO TO 90
AID(I) = .FALSE.

CONTINUE 90

C--- CONSYS DETERMINES FOR EACH SYSTEM WHICH STRESSES, STRAINS AND DISPLACEMENTS WILL BE CALCULATED.

CALL CONSYS(AID,NZEP,NZEQN,L)

C--- READ NUMBER OF POSITIONS AND SET LOOP

100 CALL NFRD(NIN,NPOS,1)
590 CONTINUE
580 CONTINUE 88 CONTINUE

DO 400 IPDS=I,NPOS
L2 = L
DO 110 I=1,3
DO 110 J=1,3
A(I,J)=0

C--- READ POINT COORDINATES AND LAYERNUMBER.

IF(ITER.GT.0) GO TO 570
CALL NFRD(NIN,LAY(IPOS),1)
CALL FFRD(NIN,AXX(IPOS),2)
CALL FFRD(NIN,AYY(IPOS),2)
CALL FFRD(NIN,DEP(IPOS),2)

IF(ITER.GT.0) GO TO 570

XTEMP(IPOS)=AXX(IPDS)
YTEMP(IPOS)=AYY(IPOS)
LAYER=LAY(IPOS)
AX=AXX(IPOS)
AY=AYY(IPOS)
DEPTH=DEP(IPOS)
ETA=ETAA(IPOS)
ETA=.0174533*ETA

IF(NLAYS.EQ.1)
LAYER = 1
GO TO 130
J-LAYER+1
J-MINO(J,M1)
DO 120 I=1,J

120 B-16 tj c..
317* IF(THICK(I).LT.TMIN) TMIN=THICK(I)  
318* CONTINUE  
319* UX=0.0  
320* UY=0.0  
321* UZ=0.0  
322* MU=NU(LAYER)  
323* FT=(I.O+MU)/E(LAYER)  
324* C ---------------------------------------------------------------------  
325* C SET LOOP FOR NUMBER OF LOADS.  
326* C -----.-----------.-------.-------------- -----------------------------  
327* DO 330 I=1,NLOAD  
328* DO 140 J=1,17  
329* INT(J)=0.0  
330* DO 150 J=1,27  
331* STRESS(J)=AID(J)  
332* C COMPUTES THE LIMITING ASPHALT STRAIN AND SUBGRADE STRAIN.  
333* IF(NLAYS.EQ.1) GO TO 160  
334* C ---------------------------------------------------------------------  
335* C EVALUATION OF THE CHARACTERISTIC FUNCTION IN MATRIX BY CALLING MA2CON.  
336* C ---------------------------------------------------------------------  
337* CALL MA2CON(TMIN,IISMO,ALK)  
338* C DETERMINATION OF POINT COORDINATES IN CYLINDRICAL COORDINATE SYSTEM WITH LOAD-AXIS AS AXIS OF SYMMETRY.  
339* IF(X(1).EQ.AX.AND.Y(I).EQ.AY) GO TO 170  
340* THETA=ATAN2C(AY-Y(1)),(AX-X(I))1-PSI(1)  
341* GO TO 180  
342* THETA=ETA-PSI(I)  
343* RADDIS=SQRT((AX-X(I))**2+(AY-Y(I)**2)  
344* WRITE(NOUT,9100) I,RADDIS,THETA  
345* R=RADDIS/RADIUS(I)  
346* Z=DEPTH/RADIUS(I)  
347* IF(NLAYS.EQ.1) GO TO 160  
348* IF(LAYER.GT.1) GO TO 210  
349* IF(Z.GT.(H(M)-ACCUR(I))) GO TO 230  
350* GO TO 200  
351* IF(Z.GT.(H(LAYER-1)-ACCUR(I)) AND Z.LT.(H(LAYER)+ACCUR(I)) GO TO 230  
352* RADI=RADIUS(I)  
353* LOAD=LDSTRS(I)  
354* HOSTRS=HOSTR(I)  
355* RLOW=R.LT.ACCUR(I)  
356* ST=SIN(THETA)  
357* B-17
C = \cos(\Theta)

CONPNT determines for each point-load configuration which integrals have to be calculated.

CALL CONPNT(R,HOSTRS,LOADZ,N2,L2)

IF(LAYER.NE.1) GO TO 250

CZ = DBLE(Z)

IF(Z.LT.ACCUR(1).AND.ABS(R-1.0).LT.ACCUR(1)) GO TO 240

ASYMPT determines the lipschitz-hankel integrals needed for the asymptotic part of the integrals, for points in the top-layer only.

CALL ASYMPT(R,ACCUR(1))

GO TO 250

FOR points at the rim of the load the lipschitz-mankel integrals can be given directly.

240

F10 M1 = 0.63662
F10 M0 = 0.5
F11 M1 = 0.5
F11 M2 = 0.42443
F10 I = 0.0
F11 0 = 0.0
F11 1 = 0.0

260

INT(J) = 0.0

270

CONTINUE

DO 270 J = 1,10

INTV(J) = K

INTV(J) = INTV(J) + INTT

280

CONTINUE

IF(INTV.EQ.0) GO TO 280

IF(NLAYS.NE.1) CALL GENDAT(1,NZEROS.R,ACC)

CALL INGRAL(2,INTV,INTT,INT)

290

CONTINUE

IF(INVT.EQ.0) GO TO 290

IF(NLAYS.NE.1) CALL GENDAT(1,NZEROS,R,ACC)

CALL INGRAL(2,INTV,INTT,INT)

INTT = INTT + INTV(J)

INTT = 0
C - CALC COMPUTES AND OUTPUTS THE STRESSES, STRAINS AND DISPLACEMENTS INDUCED BY EACH LOAD SEPARATELY.
C - COMPUTATION AND SUMMATION OF CARTESIAN COORDINATES. THE USED COORDINATE SYSTEM IS THE ONE WHEREIN POINT COORDINATES WERE STATED.

C l
UZ = UZ + V(5)

C i
CT = (AX-X(I))/RADDIS
     ST = (AY-Y(I))/RADDIS

C o
GO TO 320

C d
CT = COS(ETA)
     ST = SIN(ETA)

C y
CT2 = ST*ST
     STCT = ST*CT

C 2
A(I,1) = A(I,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(I,2) = A(I,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(I,3) = A(I,3) + V(8)*CT - V(9)*ST

C 3
A(1,1) = A(1,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(1,2) = A(1,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(1,3) = A(1,3) + V(8)*CT - V(9)*ST

C 4
A(2,1) = A(2,1)
     A(2,2) = A(2,2) + V(4)*ST2 + V(5)*CT2 + 2.0*V(7)*STCT
     A(2,3) = A(2,3) + V(9)*CT + V(8)*ST

C 5
A(3,1) = A(3,1)
     A(3,2) = A(3,2)
     A(3,3) = A(3,3) + V(6)

C 6
UX = UX + V(1)*CT - V(2)*ST
     UY = UY + V(1)*ST + V(2)*CT

C 7
IF (ABS(RADDIS).LT.ACUR(I)) GO TO 310

C 8
DO 350 J=1,3
     DO 340 I=1,3
     B(I,J) = A(I,J)

C 9
IF (NLAYS.NE.1) CALL GENDAT(0, NZEROS, R, ACC)

C 10
CALL INGRAL(IINTV, INTT, INT)

C 11
PSIO = PSI(I)

C 12
CONTINUE

C 13
CALL CALC(INT, V, R, ML, RAD, FT, LOAD, HOSTRSPSI, PSIO, Z)

C 14
IF (.NOT.N?) GO TO 330

C 15
C ----------------------------------------

C 16
TRACExA(I,1)*A(2,2)+A(3,3)
     AB = (1.0*MU)/ELAYER
     AC = MU*TRACE/ELAYER

C 17
DO 350 J=1,3
     DO 340 I=1,3
     B(I,J) = A(I,J) - AC

C 18
CONTINUE

C 19
CONTINUE

C 20
CONTINUE

C 21
CONTINUE

C 22
CONTINUE

C 23
INTV(J) = K
     INTT = INTT + 1
     CONTINUE

C 24
IF (INTT.EQ.0) GO TO 330
     IF (NLAYS.NE.1) CALL GENDAT(0, NZEROS, R, ACC)
     CALL INGRAL(IINTV, INTT, INT)

C 27
PSIO = PSIO(I)

C 28
CONTINUE

C 29
C PRINTED REPORTS THE STRESSES, STRAINS, DISPLACEMENTS, AND SCALARS INDUCED BY EACH LOAD SEPARATELY.
C - COMPUTATION AND SUMMATION OF CARTESIAN COORDINATES. THE USED COORDINATE SYSTEM IS THE ONE WHEREIN POINT COORDINATES WERE STATED.

C 30
UZ = UZ + V(5)

C 31
CT = (AX-X(I))/RADDIS
     ST = (AY-Y(I))/RADDIS

C 32
GO TO 320

C 33
CT = COS(ETA)
     ST = SIN(ETA)

C 34
CT2 = ST*ST
     STCT = ST*CT

C 35
A(I,1) = A(I,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(I,2) = A(I,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(I,3) = A(I,3) + V(8)*CT - V(9)*ST

C 36
A(1,1) = A(1,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(1,2) = A(1,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(1,3) = A(1,3) + V(8)*CT - V(9)*ST

C 37
A(2,1) = A(2,1)
     A(2,2) = A(2,2) + V(4)*ST2 + V(5)*CT2 + 2.0*V(7)*STCT
     A(2,3) = A(2,3) + V(9)*CT + V(8)*ST

C 38
A(3,1) = A(3,1)
     A(3,2) = A(3,2)
     A(3,3) = A(3,3) + V(6)

C 39
UX = UX + V(1)*CT - V(2)*ST
     UY = UY + V(1)*ST + V(2)*CT

C 40
IF (ABS(RADDIS).LT.ACUR(I)) GO TO 310

C 41
CT = (AX-X(I))/RADDIS
     ST = (AY-Y(I))/RADDIS

C 42
GO TO 320

C 43
CT = COS(ETA)
     ST = SIN(ETA)

C 44
CT2 = ST*ST
     STCT = ST*CT

C 45
A(I,1) = A(I,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(I,2) = A(I,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(I,3) = A(I,3) + V(8)*CT - V(9)*ST

C 46
A(1,1) = A(1,1) + V(4)*CT + V(5)*ST2 - 2.0*V(7)*STCT
     A(1,2) = A(1,2) + V(7)*(CT2-ST2) + (V(4)-V(5))*STCT
     A(1,3) = A(1,3) + V(8)*CT - V(9)*ST

C 47
A(2,1) = A(2,1)
     A(2,2) = A(2,2) + V(4)*ST2 + V(5)*CT2 + 2.0*V(7)*STCT
     A(2,3) = A(2,3) + V(9)*CT + V(8)*ST

C 48
A(3,1) = A(3,1)
     A(3,2) = A(3,2)
     A(3,3) = A(3,3) + V(6)

C 49
UX = UX + V(1)*CT - V(2)*ST
     UY = UY + V(1)*ST + V(2)*CT

C 50
CONTINUE

C 51
CONTINUE

C 52
CONTINUE

C 53
CONTINUE

C 54
CONTINUE

C 55
CONTINUE

C 56
CONTINUE

C 57
CONTINUE

C 58
CONTINUE

C 59
CONTINUE

C 60
CONTINUE

C 61
CONTINUE

C 62
CONTINUE

C 63
CONTINUE

C 64
CONTINUE

C 65
CONTINUE

C 66
CONTINUE

C 67
CONTINUE

C 68
CONTINUE

C 69
CONTINUE

C 70
CONTINUE

C 71
CONTINUE

C 72
CONTINUE

C 73
CONTINUE

C 74
CONTINUE

C 75
CONTINUE

C 76
CONTINUE

C 77
CONTINUE

C 78
CONTINUE

C 79
CONTINUE

C 80
CONTINUE

C 81
CONTINUE

C 82
CONTINUE

C 83
CONTINUE

C 84
CONTINUE

C 85
CONTINUE

C 86
CONTINUE

C 87
CONTINUE

C 88
CONTINUE

C 89
CONTINUE

C 90
CONTINUE

C 91
CONTINUE

C 92
CONTINUE

C 93
CONTINUE

C 94
CONTINUE

C 95
CONTINUE

C 96
CONTINUE

C 97
CONTINUE

C 98
CONTINUE

C 99
CONTINUE

C 100
JACOBI COMPUTES PRINCIPAL VALUES AND DIRECTIONS OF TOTAL STRESSES AND STRAINS. THE PRINCIPAL VALUES ARE SORTED TO MAGNITUDE BY CALLING IN ESORT.

CALL JACOBI(AHH,3,1,NL2)
CALL ESORT(A,HJ,2,1,1.0)

DETERMINATION OF MAX. SHEAR STRESSES AND STRAINS WITH THEIR DIRECTIONS AND DETERMINATION OF MIDPOINTS OF THE MOHR'S CIRCLE.

DO 370 J=1,3
    C(J) = A(I,J)+A(J,2)-A(3,3)
    C(J+5) = (H(H(J,1)-H(H(J,3))/V2
    C(J+9) = (H(H(J,1)-H(H(J,2))/V2
    C(J+14) = (H(H(J,1)+H(H(J,2))/V2
    C(J+18) = (H(H(J,2)-H(H(J,3))/V2
    C(J+23) = (H(H(J,2)+H(H(J,3))/V2
    C(J+27) = (H(H(J,2)+H(H(J,3))/V2

CONTINUE

DO 380 I1=1,3
    C(I+30) = C(I+12)
    C(I+12) = C(I+21)
    C(I+21) = C(I+30)

CONTINUE

IF(C(I)) GT C(22) GO TO 385

CONTINUE

385 CONTINUE

ITER BLOCK

IF(ISKIP.GT.0) GO TO 699

IF(EKEY.EQ.3 ) GO TO 603

IF(EKEY.EQ.0.0) CALL NFRD(S,IDNM,1)

IF(ABS(C(I)) LT STRL2) GO TO 400

WRITE(*,915) ALOAD,PS12,AA,BB,RN,ABSC1,STRL2

B-21
IF(EKEY.EQ.2)WRITE(NOUT,916)ALOAD,PSI2,ES,AS,BS,ABSC1,STRL2
TAWGHT=(2.0*NLOAD*ALOAD)/0.95
WRITE(NOUT,911)TAWGHT
HP053=NLOAD
CALL POST(X,Y,NPOS3,LAY,AXX,AYY,DEP,ETAA)
ITER=1
ISkip=1
GO TO 580
TAWGHT=(2.0*NLOAD*ALOAD)/0.95
WRITE(NOUT,911)TAWGHT
NPOS3=NLOAD
CALL POST(X,Y,NPOS3,LAY,AXX,AYY,DEP,ETAA)
ITER=1
ISkip=1
GO TO 580
CONTINUE
C RIGID OVERLAY
IF(EKEY2.NE.2)GO TO 640
IF(ABS(ABS(A(I,1))).LT.STSL)GO TO 690
ABSRS=ABS(A(1,1))
WRITE(NOUT,912)DSM,ABSRS,STSL,THICK(1)
NPOS3=NLOAD
CALL POST(X,Y,NPOS3,LAY,AXX,AYY,DEP,ETAA)
ITER=1
ISkip=1
GO TO 580
CONTINUE
C RIGID ALLOWABLE LOAD
IF(ABS(A(I,1))).LT.STSL)GO TO 680
RSTS=ABS(A(I,1))
WRITE(NOUT,913)ALOAD,DSM,ABSRS,RSTS,STSL,THICK(1)
NPOS3=NLOAD
CALL POST(X,Y,NPOS3,LAY,AXX,AYY,DEP,ETAA)
ITER=1
ISkip=1
GO TO 580
CONTINUE
C INCREMENT LOAD
DO 670 17=NLOAD
LDSTRS(17)=ALOAD+ALIN
LDSTRS(17)=LDSTRS(17)/CAREA
ALOAD=ALOAD*ALIN
LOAD=LDSTRS(1)
PSI2=LOAD
ITER=1
GO TO 580
CONTINUE
B-22
C FLEXIBLE OVERLAY

GO TO (631,612),IPOS

631 CONE=C(1)

GO TO 690

IF(ABS(CONE).GE.STRL2 .OR. ABS(E(3,3)).GE.STRL) GO TO 690

ABS((2,3))=ABS(E(3,3))

WRITE(NOUT,914) DSMABC1,STRL2,ABSV12,STRL,THICK(l)

NPOS3=NLOAD

CALL POST(X,YNPOS3,LAYAXX,AYY,DEP,ETAA)

ITER=1

ISKIP=1

GO TO 580

CONTINUE

INCREMENT THICKNESS

THICK(C(B))=ATICK+ATLIN

ATHICK=ATHICK+ATLIN

DO 666 IT=NPOS

DEP(IT)=DEP(IT)+ATLIN

ITER=

GO TO 580

CONTINUE

C OUTPUT FOR PRINCIPAL STRESSES,ETC.MAXIMUM

WRITE(NOUT,9130) A(1,1),C(1),HH(1,1),HH(2,1),HH(3,1),

+ A(2,2),C(2),HH(1,2),HH(2,2),HH(3,2),

+ A(3,3),C(3),HH(1,3),HH(2,3),HH(3,3),

+ (C(B),I4,301

BX = (A(1,1)*C(1)+A(2,2)*C(2)+A(3,3)*C(3))*0.5

BY = 0.6666667*AB*(C(4)*C(4)+C(13)*C(13)+C(22))*C(22)

WRITE(NOUT,9200) BX,BY

CONTINUE

READ(NOUT,9140) J

WRITE(NOUT,9180) J

WRITE(NOUT,9190)

FOR SYSTEMS FOR WHICH IT IS CLEAR THAT

MISTAKES OCCUR IN THE INPUT CARDS THE REQUEST AND POINT INPUT CARDS ARE SKIPPED.

PROGRAM PROCEEDS BY TAKING NEXT SYSTEM.

READ(NIN,9150)

READ(NIN,9130) A(1,1),C(1),HH(1,1),HH(2,1),HH(3,1),

+ A(2,2),C(2),HH(1,2),HH(2,2),HH(3,2),

+ A(3,3),C(3),HH(1,3),HH(2,3),HH(3,3),

+ (C(B),I4,301

CONTINUE

GO TO 460

WRITE(NOUT,9140) J

GO TO 460

WRITE(NOUT,9180) J

GO TO 460

WRITE(NOUT,9190)

READ(NIN,9150) NPOS

DD 450 I=1,NPOS

READ (NIN,9150)
680=   460 CONTINUE
681=   WRITE(OUT,9160)
682=   STOP
683=   900 FORMAT(1H1/,5(2H*),/1'FLEXIBLE PAVEMENT ALLOWABLE LOAD',/2'LOAD ',5(2H*),/60(1H*)/,/3'STRL(SUBGRADE LIMITING STRAIN) = ',F15.8/,/4'STRL2(ASPHALT LIMITING STRAIN) = ',F15.8/,/5'ALOAD = ',F15.0/,/ALIN = ',F15.0/,/660(1H*)/,///)
684=   901 FORMAT(1H1/,5(2H*),/150RIGID PAVEMENT ALLOWABLE LOAD',/700=   B5(2H*),/60(1H*)/,/20X,'FS = ',F6.0/,/701=   1 20X,'DSM = ',F6.0/,/702=   2 20X,'ALOAD = ',F6.0/,/703=   3 20X,'ATLM = ',F6.0/,/704=   4 20X,'STSL = ',F15.6/60(1H*)///)
685=   902 FORMAT(1H1/,5(2H*),1.19HD VERLAY O.V.
686=   903 FORMAT(///60(1H*)/,/20X,'DSM = ',F6.0/,/700=   A 20X,'SNL = ',F12.0/,/701=   1 20X,'ATHICK = ',F6.2/,/710=   2 20X,'ATLIN = ',F6.2/,/711=   44X,'LIMITING SUBGRADE STRAIN = ',F15.8/,/712=   55X,'LIMITING ASPHALT STRAIN = ',F15.8/60(1H*)///)
687=   904 FORMAT(1H1/,5(2H*),1.29D VERLAY O.V.
688=   905 FORMAT(///60(1H*)/,/20X,'DSM = ',F6.0/,/706=   A 20X,'SNL = ',F12.0/,/717=   B 20X,'FS = ',F6.0/,/718=   1 20X,'ATHICK = ',F6.2/,/719=   2 20X,'ATLIN = ',F6.2/,/720=   3 20X,'STSL = ',F15.8/60(1H*)///)
689=   906 FORMAT('MAXIMUM NORMAL STRAIN = ',F15.8/3F15.2/) 00016720
690=   907 FORMAT('VERTICAL STRAIN = ',F15.8/3F15.2/) 00016730
691=   908 FORMAT('MAXIMUM NORMAL STRESS = ',F15.8/3F15.2/) 00016740
692=   909 FORMAT('/20X,'ALOAD = ',F10.0/,/22X,'PSI = ',F10.2/,/110X,'AA = ',F12.8/,/BB = ',F12.8/,/RN = ',F12.8/,/2/8(1H*)/,/VSTR = ',F12.8/8(1H*)///)
693=   910 FORMAT('/20X,'ALOAD = ',OF10.0/,/22X,'PSI = ',OF10.2/,/110X,'ES = ',OF12.3X,'XS = ',/20F6.0,5X,'AS = ',/0PF12.6/,/95 = ',OF12.6/,/A16(1H*)/,/VSTR = ',OF12.6/,/3' STRL = ',OF12.8/16(1H*)///)
694=   911 FORMAT('/20X,'TOTAL ALLOWABLE WEIGHT = ',F10.0/) 00017100
695=   912 FORMAT(1H1/,60(1H*)/,/20X,'DSM = ',F6.0/,/20X,'ABSRS = ',F15.8/,/20X,'STSL = ',F15.8/,/20X,'FINAL THICKNESS = ',F8.2/,/60(1H*)/,/60(1H*)///)
696=   913 FORMAT(1H1/,60(1H*)/,/20X,'ALOAD = ',F10.0/,/20X,'PSI = ',F8.0/,/20X,'FS = ',F6.0/) 00017120

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3 20X, 'DSM = ',F6.0,/, 0001720
4 20X, 'STSL = ',F15.8,/, 0001720
5 20X, 'STSL = ',F15.8,/, 0001720
6 /60(1H*),/60(1H*)/0001720
7 916 FORMAT('1H1,60(1H*),/60(1H*)//,20X,'DSM = ',F6.0,/, 0001720
8 A 20X, 'ABC1 = ',F15.8,/, 0001720
9 B 20X, 'STRL2 = ',F15.8,/, 0001720
10 2 20X, 'STRL = ',F15.8,/, 0001720
11 3 20X, 'FINAL. THICKNESS = ',F8.2,/, 0001720
12 4 /60(1H*),/60(1H*)/0001720
13 915 FORMAT(',//20X,'ALDAD = ',F10.0,/,22X,'PSI = ',F10.2,/, 0001720
14 110X,*AA = ',F12.8,/,BBO',F12.8,/, 0001720
15 21BS = *',OPF12.6,/,11(1H*),ABSCI = ',OPF12.8,/, 0001720
16 916 FORMAT(',//20X,'ALDAD = ',F10.0,/,22X,'PSI = ',F10.2,/, 0001720
17 1,1OX,'ES = ',OPF12.0,/,11X,'XS = ',OPF8.0,/, 0001720
18 3,'STRL2 = ',BPF12.8,/,16(1H*),/0001720
19 +18X,'BB',9X,'BBB III SSS',14X,'AAA',9X,'AAA RR',9X,'RR'/0001720
20 +18X,'BB',8X,'BBB III SSS',14X,'AAA',9X,'AAA RR',9X,'RR'/0001720
21 +18X,'BB',7X,'BBB III',5X,'SSS AA',9X,'AA RR',6X,'RR'/0001720
22 +18X,'BB',6X,'BBB III',5X,'SSS AA',9X,'AA RR',6X,'RR'/0001720
23 +18X,'BB',5X,'BBB III',5X,'SSS AA',9X,'AA RR',6X,'RR'/0001720
24 +18X,'BB',4X,'BBB III',5X,'SSS AA',9X,'AA RR',6X,'RR'/0001720
25 43X,'BB',7X,'BBB III',5X,'SSS AA',9X,'AA RR',6X,'RR'/0001720
26 '/16(LH*),'ABSCI = ',BPF12.8,/,16(lH*)////)0001720
27 3. STRL2 = ',BPF12.8,/,16(lH*)////)0001720
28 9000 FORMAT('1H1,17X,11('B'),3X,'R',3X,11('R'),5X,13('A'),3X,11('R'),/ 0001720
29 5X,11('S'),5X,13('A'),/0001720
30 +I8X,11('B'),5X,11('S'),5X,13('A'),/0001720
31 7X,11('S'),5X,13('A'),/0001720
32 7X,11('S'),5X,13('A'),/0001720
33 7X,11('S'),5X,13('A'),/0001720
34 7X,11('S'),5X,13('A'),/0001720
35 7X,11('S'),5X,13('A'),/0001720
36 7X,11('S'),5X,13('A'),/0001720
37 7X,11('S'),5X,13('A'),/0001720
38 7X,11('S'),5X,13('A'),/0001720
39 7X,11('S'),5X,13('A'),/0001720
40 7X,11('S'),5X,13('A'),/0001720
41 7X,11('S'),5X,13('A'),/0001720
42 7X,11('S'),5X,13('A'),/0001720
43 7X,11('S'),5X,13('A'),/0001720
44 7X,11('S'),5X,13('A'),/0001720
45 +E LOADS IN STRESS UNITS') 0001720
46 9050 FORMAT(4EI2.6) 0001720
47 9060 FORMAT(26A3,A2) 0001720
48 9070 FORMAT('NOTE THAT INCORRECT SPELLING HAS NOT STOPPED THE EVALUATION OF STRESS',4X,A3) 0001720
49 9080 FORMAT(12,4E12.6) 0001720
50 9090 FORMAT(4EI2.6) 0001720
51 9100 FORMAT('NOTE THAT INCORRECT SPELLING HAS NOT STOPPED THE EVALUATION OF STRESS',4X,A3) 0001720
52 9110 FORMAT('NOTE THAT INCORRECT SPELLING HAS NOT STOPPED THE EVALUATION OF STRESS',4X,A3) 0001720
53 9120 FORMAT('NOTE THAT INCORRECT SPELLING HAS NOT STOPPED THE EVALUATION OF STRESS',4X,A3) 0001720
54 *'UX',10X,'UY',10X,'UZ') 00017740
SUBROUTINE SYSTEM(ISYS, E, HU, THICK, AK, NLAYS, M, NLOADLDSTRS, NOSTR, IALK, RADIUS, X, Y, PSI, ISMO.IRED)  

C------------------------------------------------------------------------------
C THIS SUBROUTINE OUTPUTS ALL PHYSICAL DATA OF THE MULTI-LAYERED SYSTEM AND ALL DATA ON CONFIGURATION AND MAGNITUDE OF THE LOADS.
C------------------------------------------------------------------------------

INTEGER ROUGH(2), SMOOTH(2), ISMTH(2)
REAL E(10), NU(10), THICK(9), AK(9), LDSTRS(10), HOSTR(10), IRADZUS(10), X(10), Y(10), PSI(10)
COMMON/TAPE/NOUT
DATA ROUGH, SMOOTH/'ROU','GN ' 'SMO','OTH'/

WRITE(NOUT, 1001) ISYS
IF( IRED.EQ.0) WRITE(NOUT, 1002)
IF( IRED.NE.0) WRITE(NOUT, 1007)
IF(NLAYS.EQ.1) GO TO 40
DO 30 I = IM
   IF(ISMO.EQ.1) GO TO 10
   ISMTN(1) = ROUGH(I)
   ISMTN(2) = ROUGH(I)
   IF(ALK(I).LT.100.0) GO TO 20
   ISMTH(1) = SMOOTH(I)
   ISMTH(2) = SMOOTH(I)
   IF(ISMO.EQ.0) WRITE(NOUT, 1002)
   WRITE(NOUT, 1007)
   IF(LNAYS.EQ.1) GO TO 40
   DO 50 I = 1, M
      IF(ISMO.EQ.1) GO TO 10
      ISMTH(1) = ROUGH(I)
      ISMTH(2) = ROUGH(I)
      IF(ALK(I).LT.100.0) GO TO 20
      ISMTH(1) = SMOOTH(I)
      ISMTH(2) = SMOOTH(I)
      IF(ISMO.EQ.0) WRITE(NOUT, 1002)
      WRITE(NOUT, 1007)
      WRITE(NOUT, 1003) I, ISMTH(1), ISMTH(2), E(I), NU(I), THICK(I), AK(I)
   CONTINUE
   WRITE(NOUT, 1004) NLAYS, E(NLAYS), NU(NLAYS)
   WRITE(NOUT, 1005) 0
   WRITE(NOUT, 1006) I, LDSTRS(I), HOSTR(I), RADIUS(I), X(I), Y(I), PSI(I)
   CONTINUE
   WRITE(NOUT, 1007) 0
   WRITE(NOUT, 1008)
   IF(LNAYS.EQ.1) GO TO 40
   DO 50 I = 1, NLOAD
      WRITE(NOUT, 1009) I, LDSTRS(I), HOSTR(I), RADIUS(I), X(I), Y(I), PSI(I)
   CONTINUE
   WRITE(NOUT, 1010) 0
   WRITE(NOUT, 1011) 0
   WRITE(NOUT, 1012) 0
   WRITE(NOUT, 1013) 0
   WRITE(NOUT, 1014) 0
   WRITE(NOUT, 1015) 0
   WRITE(NOUT, 1016) 0
   WRITE(NOUT, 1017) 0
   WRITE(NOUT, 1018) 0
   WRITE(NOUT, 1019) 0
   WRITE(NOUT, 1020) 0
   WRITE(NOUT, 1021) 0
   WRITE(NOUT, 1022) 0
   WRITE(NOUT, 1023) 0
   WRITE(NOUT, 1024) 0
   WRITE(NOUT, 1025) 0
   WRITE(NOUT, 1026) 0
   WRITE(NOUT, 1027) 0
   WRITE(NOUT, 1028) 0
   WRITE(NOUT, 1029) 0
   WRITE(NOUT, 1030) 0
   WRITE(NOUT, 1031) 0
   WRITE(NOUT, 1032) 0
   WRITE(NOUT, 1033) 0
   WRITE(NOUT, 1034) 0
   WRITE(NOUT, 1035) 0
   WRITE(NOUT, 1036) 0
   WRITE(NOUT, 1037) 0
   WRITE(NOUT, 1038) 0
   WRITE(NOUT, 1039) 0
   WRITE(NOUT, 1040) 0
   WRITE(NOUT, 1041) 0
   WRITE(NOUT, 1042) 0
   WRITE(NOUT, 1043) 0
   WRITE(NOUT, 1044) 0
   WRITE(NOUT, 1045) 0
   WRITE(NOUT, 1046) 0

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SUBROUTINE MACONII(ISMO,ALK,NSYS)

C ----------
C THIS SUBROUTINE CALCULATES CONSTANTS USED IN SUBROUTINE MATRIX TO BUILD UP VARIOUS MATRICES.
C THE CONSTANTS ARE STORED IN COMMON/INDATA/. NUMERICAL STABILITY OF SOLUTION PROCEDURE IS TESTED BY CALLING IN# MATRIX WHEN INSTABILITY HAS TO BE EXPECTED THE SMOOTH CALCULATION PROCEDURE IS CHosen BY TAKING ISMO = 1 AND NSYS IS SET EQUAL I.

C ----------
REAL K1,K2,K3(10),K4(10),K5,K6,HU,AL00,ACCUR(3) *ALK(9)
COMMON/INDATA/XMAX, Al(9) .01(9) .01(9) .0(9) ,EE(9) ,F(9) .019) .N1(9) .0001850
101(9) .K119) .K2(9) .K6( 10),BE(9),BU(9) .BUU(9) ,BMU(9) .82U(9) ,B2UU(9) .0001859
2J2(9).J1 .T2(10).SS(2. lO).G012(9),G021(9).G022(9),0122(9),
3H012(9) .H022(9) .Hl22(9) ,D012(9) .0022(9) .0011(9) .0012(9) .E012(9)
4F002(9),F112(9).F022(9),CC(4.2,9),DD(2,2,9),FF(2,2,9),GG(2,2,9),HH(2,2,9),RR(4,2,10),0D2(9),G20(9),G012(9),G021(9).G21(9).H20(9),H021(9),G22(10),
5HH(2,2, 101,RR(4,2,10),0D2(9),G20(9),G012(9),G021(9),G21(9).H20(9),H021(9),G22(10),
6HH2( 10) ,Q011(9) .Q111(9) .Q012(9) .Q112(9) ,Q212(9).Q022(9) .Q122(9) .
8Z122,Z222,K*

C ----------
C COMMON/TAPE/NOUT
C NSYS = 0
C IFS(NLAYS,EQ.1) GO TO 10
C GG(1,1,1) = -1.0
C GG(2,1,1) = 1.0
C GG(1,2,1) = 1.0-2.0*Nu(1)
C GG(2,2,1) = 2.0*Nu(1)
C HH(1,1,1) = 1.0
C HH(1,2,1) = GG(1,1,1)
C HH(2,1,1) = 1.0
C HH(2,2,1) = GG(2,2,1)
C RR(1,1,NLAYS) = 0.0
C RR(2,1,NLAYS) = 0.0
C RR(1,2,NLAYS) = 0.0
C RR(2,2,NLAYS) = 0.0
C RR(3,1,NLAYS) = 1.0
C RR(3,2,NLAYS) = 0.0
C
C ----------
C 10 RETURN
C 11 FORMAT(///8X, 'LOAD' ,5X, 'NORMAL' ,7X, 'SHEAR' ,5X, 'RADIUS OF', 7X, 'LOAD00018280
C 13 FORMAT(///8X, 'X', 'Y', 7X, 'DIRECTION'/)
C 14 FORMAT(10X, I2,2X,6E12.4)
C 16 FORMAT(5(/I,8X.'LAYER'.4X,'CALCULATION'.2X,'YOUNG''S'.3X,'THICKNESS',3X, 'REDUCED' ,8X,'NUMBER',3X,'METHOD',7X,'MOD00018350
C 17 RETURN
C 18 END
C
C SUBROJTINE MACONII(SM0,AL,NSYS)

C ----------
C THIS SUBROUTINE CALCULATES CONSTANTS USED IN SUBROUTINE MATRIX TO BUILD UP VARIOUS MATRICES.
C THE CONSTANTS ARE STORED IN COMMON/INDATA/. NUMERICAL STABILITY OF SOLUTION PROCEDURE IS TESTED BY CALLING IN# MATRIX WHEN INSTABILITY HAS TO BE EXPECTED THE SMOOTH CALCULATION PROCEDURE IS CHosen BY TAKING ISMO = 1 AND NSYS IS SET EQUAL I.

C ----------
REAL K1,K2,K3(10),K4(10),K5,K6,HU,AL00,ACCUR(3) *ALK(9)
COMMON/INDATA/XMAX, Al(9) .01(9) .01(9) .0(9) ,EE(9) ,F(9) .019) .N1(9) .0001850
101(9) .K119) .K2(9) .K6( 10),BE(9),BU(9) .BUU(9) ,BMU(9) .82U(9) ,B2UU(9) .0001859
2J2(9).J1 .T2(10).SS(2. lO).G012(9),G021(9).G022(9),0122(9),
3H012(9) .H022(9) .Hl22(9) ,D012(9) .0022(9) .0011(9) .0012(9) .E012(9)
4F002(9),F112(9).F022(9),CC(4.2,9),DD(2,2,9),FF(2,2,9),GG(2,2,9),HH(2,2,9),RR(4,2,10),0D2(9),G20(9),G012(9),G021(9).G21(9).H20(9),H021(9),G22(10),
5HH(2,2, 101,RR(4,2,10),0D2(9),G20(9),G012(9),G021(9),G21(9).H20(9),H021(9),G22(10),
6HH2( 10) ,Q011(9) .Q111(9) .Q012(9) .Q112(9) ,Q212(9).Q022(9) .Q122(9) .
8Z122,Z222,K*

C ----------
C COMMON/TAPE/NOUT
C NSYS = 0
C IFS(NLAYS,EQ.1) GO TO 10
C GG(1,1,1) = -1.0
C GG(2,1,1) = 1.0
C GG(1,2,1) = 1.0-2.0*Nu(1)
C GG(2,2,1) = 2.0*Nu(1)
C HH(1,1,1) = 1.0
C HH(1,2,1) = GG(1,1,1)
C HH(2,1,1) = 1.0
C HH(2,2,1) = GG(2,2,1)
C RR(1,1,NLAYS) = 0.0
C RR(2,1,NLAYS) = 0.0
C RR(1,2,NLAYS) = 0.0
C RR(2,2,NLAYS) = 0.0
C RR(3,1,NLAYS) = 1.0
C RR(3,2,NLAYS) = 0.0
C
C ----------
C 10 RETURN
C 11 FORMAT(///8X, 'LOAD' ,5X, 'NORMAL' ,7X, 'SHEAR' ,5X, 'RADIUS OF', 7X, 'LOAD00018280
C 13 FORMAT(///8X, 'X', 'Y', 7X, 'DIRECTION'/)
C 14 FORMAT(10X, I2,2X,6E12.4)
C 16 FORMAT(5(/I,8X.'LAYER'.4X,'CALCULATION'.2X,'YOUNG''S'.3X,'THICKNESS',3X, 'REDUCED' ,8X,'NUMBER',3X,'METHOD',7X,'MOD00018350
C 17 RETURN
C 18 END
C
C SUBROJTINE MACONII(SM0,AL,NSYS)

C ----------
C THIS SUBROUTINE CALCULATES CONSTANTS USED IN SUBROUTINE MATRIX TO BUILD UP VARIOUS MATRICES.
C THE CONSTANTS ARE STORED IN COMMON/INDATA/. NUMERICAL STABILITY OF SOLUTION PROCEDURE IS TESTED BY CALLING IN# MATRIX WHEN INSTABILITY HAS TO BE EXPECTED THE SMOOTH CALCULATION PROCEDURE IS CHosen BY TAKING ISMO = 1 AND NSYS IS SET EQUAL I.
RR(4.1,NLAYS) = 0.0 0018810
RR(4.2,NLAYS) = 1.0 0018820
RR(4.1,NLAYS) = 0.0 0018830
RR(4.2,NLAYS) = 1.0 0018840
GG2(I) = 1.0 0018850
WZ2(I) = -1.0 0018860
K5(I) = 1.0-2.0*NU(I) 0018870
IF(NLAYS.EQ.1) GO TO 70 0018880
K = 0 0018890
K6(I) = 4.0*(1.0-NU(I)) 0018900
DO 30 J=1,M 0018910
KI(J)=(1.0+NU(J+1))*E(J)/((1.0+NU(J))*E(J+1)) 0018920
J2(J) = 1.0-KI(J) 0018930
K6(J+1) = 4.0*(1.0-NU(J+1)) 0018940
A1(J) = K6(J)-J2(J) 0018950
B1(J) = J2(J)+KI(J)*K6(J+1) 0018960
CI(J) = 2.0*K2(J) 0018970
D(J) = J2(J)*(1.0-4.0*NU(J)) 0018980
EE(J) = J2(J)*(1.0+K4(J))-6.0*K3(J) 0018990
F(J) = A1(J)-B1(J) 0019000
Hl(J) = 4.0*K2(J)*(NU(J+1)-NU(J)) 0019010
II(J) = D(J)-Hl(J) 0019020
CONTINUE 0019030
K5(M+I) = 1.0-2.0*NU(M+I) 0019040
IF(ISMO.EQ.1) GO TO 70 0019050
IF(ALK(I).LT.100.0) GO TO 50 0019060
CONTINUE 0019070
GO TO 70 0019080
C-----------------------------------------------------------------------
C CALCULATION OF CONSTANTS ONLY NEEDED IN MATRIX FOR STABILITY TEST.
C-----------------------------------------------------------------------
50 TMIN = 1.0E+10 0019090
NTELL = 2 0019100
DUMMY = 0.0 0019110
LAYER = NLAYS 0019120
T2(NLAYS) = 0.0 0019130
DO 60 K = 1,M 0019140
IF(THICK(K).LT.TMIN) TMIN = THICK(K) 0019150
DUMMY = DUMMY+THICK(K) 0019160
H(K) = DUMMY/RADIUS(1) 0019170
60 CONTINUE 0019180
CALL MA2CON(TMIN,IISMO,ALK) 0019190
TX = 6.6*RADIUS(1)/TMIN 0019200
XMAX = TX+1.0 0019210
C------------------------------------------------------------------------
C TEST ON NUMERICAL STABILITY OF THE SOLUTION. 0019220
950 XMAX = TX+1.0 0019300
951 C------------------------------------------------------------------------
952 C
PROCEDURE TO BE FOLLOWED FOR THIS SYSTEM BY CALLING IN THE MATRIX SUBROUTINE NEITHER WITH NTELL = 2.

AFTER TEST THE SMOOTH OR ROUGH CALCULATION IS CHOSEN.

TEST IS ONLY NECESSARY IF NOT DIRECTLY CHOSEN.

THE SMOOTH CALCULATION PROCEDURE HAS BEEN CHOSEN BY ISMO = 1.

-------------------------------------------------------------------------

CALL MATRIX(TX,1,NTELL)

IF(NTELL.EQ.2) GO TO 70

ISMO = 1

NSYS = I

WRITE(NOUT,1001) r;

RETURN

1001 FORMAT(' THE MORE STABLE SMOOTH CALCULATION PROCEDURE HAS BEEN CHOOSEN.'

END

SUBROUTINE CONSYS(AID,NZEP,NZEQ,N,L)

THIS SUBROUTINE DETERMINES FOR EACH SYSTEM THE CYLINDRICAL COMPONENTS NEEDED FOR COMPUTATION OF THE REQUIRED CRITICALS, STRAINS AND DISPLACEMENTS.

COMPONENTS OF CRITICALS, STRAINS AND DISPLACEMENTS THAT CAN BE COMPUTED WITH THE INTEGRALS.

COMPUTATION OF THE REQUIRED CARTESIAN COMPONENTS NEEDED FOR THIS SUBROUTINE DETERMINES FOR EACH SYSTEM THE CYLINDRICAL COMPONENTS NEEDED FOR COMPUTATION OF THE REQUIRED CRITICALS, STRAINS AND DISPLACEMENTS.

LOGICAL AID(27),NZEP,NZEQ,EPS(5),NL

INTEGER JARG(6,14)

DATA JARG/

1 4, 5, 7, 18, 19, 21, 6, 9, 20, 22, 0, 0, 10, 11, 13, 23, 24, 26, 0, 0,

214, 15, 25, 27, 0, 0, 1, 2, 16, 17, 0, 0, 5, 10, 12, 0, 0, 0, 0,

3 4, 10, 12, 0, 0, 0, 4, 5, 10, 0, 0, 0, 4, 6, 12, 0, 0, 0,

4 4, 5, 12, 0, 0, 0, 16, 17, 0, 0, 0, 16, 19, 21, 23, 24, 26, 0, 0,

5 23, 24, 26, 0, 0, 0, 20, 22, 25, 27, 0, 0/.

EPS(1) = AID(18).OR.AID(19).OR.AID(21)

EPS(2) = AID(20).OR.AID(22)

EPS(3) = AID(23).OR.AID(24).OR.AID(26)

EPS(4) = AID(25).OR.AID(27)

EPS(5) = AID(16).OR.AID(17)

DO 10 I = 1, 5

IF(.NOT.EPS(I)) GO TO 10

CALL LOGSET(JARG(I),AID)

10 CONTINUE

LOGICAL AID(10),NZEP,NZEQ,AID(11),TRUE.

AID(AID(10)).AND..NOT.NZEQ)

AID(AID(6)).AND..NOT.NZEQ)

AID(AID(4)). CALL LOGSET(JARG(1), AID)

AID(AID(10)). AID(11) = TRUE.

AID(AID(5)). AID(11) = TRUE.

AID(AID(12)). AID(6) = TRUE.

B-29
0104* IF(AID(8)) AID(14)*.TRUE. 00019870
0107* IF(AID(16)) AID(8)*.TRUE. 00019880
0108* IF(AID(5).AND.AID(6)) CALL LOGSET(JARG(1,7),AID) 00019890
0109* IF(AID(11).AND.AID(12)) CALL LOGSET(JARG(1,8),AID) 00019900
0110* IF(.NOT.NZEQ) GO TO 20 00019910
0111* IF(AID(7)) AID(13)*.TRUE. 00019920
0112* IF(AID(13)) AID(7)*.TRUE. 00019930
0113* IF(AID(9)) AID(15)*.TRUE. 00019940
0114* IF(AID(5).AND.AID(10)) CALL LOGSET(JARG(1,9),AID) 00019950
0115* IF(AID(6).AND.AID(10)) CALL LOGSET(JARG(1,10),AID) 00019960
0117* IF(AID(11).AND.AID(2)) CALL LOGSET(JARG(1,11),AID) 00019970
0118* IF(AID(4).AND.AID(7)) CALL LOGSET(JARG(1,12),AID) 00019980
0119* IF(AID(7).AND.AID(10)) CALL LOGSET(JARG(1,13),AID) 00019990
0120* IF(AID(8).AND.AID(9)) CALL LOGSET(JARG(1,14),AID) 00020000
0121* GO TO 30 00020010
0122* 20 IF(AID(1)) CALL LOGSET(JARG(1,11),AID) 00020020
0123* IF(AID(4)) CALL LOGSET(JARG(1,12),AID) 00020030
0124* IF(AID(8)) CALL LOGSET(JARG(1,14),AID) 00020040
0125* 30 N = .FALSE. 00020050
0126* L = .TRUE. 00020060
0128* DO 50 I = 18,27 00020080
0129* IF(AID(1)) GO TO 40 00020090
0130* L = .FALSE. 00020100
0131* GO TO 50 00020110
0132* 40 N = .TRUE. 00020120
0133* 50 CONTINUE 00020130
0134* RETURN 00020140
0135* END 00020150
0136* SUBROUTINE LOGSET(I,LOG) 00020160
0137* THIS SUBROUTINE CALLED IN BY CONSYS AND CONPNT. SETS THE LOGICAL VARIABLES LOG(K) 00020170
0138* TRUE FOR THE K-VALUES STORED IN THE ARGUMENT I. 00020180
0139* LOGICAL LOG(1) 00020190
0140* INTEGER I(1) 00020200
0141* DO 10 I = 1,6 00020210
0142* IF(I(I).EQ.0) GO TO 20 00020220
0143* LOG(I)=.TRUE. 00020230
0144* K=I(L) 00020240
0145* 10 CONTINUE 00020250
0146* RETURN 00020260
0147* END 00020270
0148* SUBROUTINE MA2CON(TMIN,I.ISMO,ALK) 00020280
0149* THIS SUBROUTINE CALCULATES CONSTANTS USED IN SUBROUTINE MATRIX TO BUILD UP VARIOUS MATRICES. THESE CONSTANTS ALL DEPENDENT ON ALK(J) AND / OR RADIUS(I). ARE STORED IN COMMON/INDATA. 00020290
0150* LOGICAL LOG(1) 00020300
0151* INTEGER I(1) 00020310
0152* DO 10 I = 1,6 00020320
0153* IF(I(I).EQ.0) GO TO 20 00020330
0154* LOG(I)=.TRUE. 00020340
0155* K=I(L) 00020350
0156* 10 CONTINUE 00020360
0157* RETURN 00020370
0158* END 00020380
0159* SUBROUTINE MA2CON(MIN,I.ISMO,ALK) 00020390
0160* THIS SUBROUTINE CALCULATES CONSTANTS USED IN SUBROUTINE MATRIX TO BUILD UP VARIOUS MATRICES. THESE CONSTANTS ALL DEPENDENT ON ALK(J) AND / OR RADIUS(I). ARE STORED IN COMMON/INDATA. 00020400
0161* LOGICAL LOG(1) 00020410
0162* INTEGER I(1) 00020420
0163* DO 10 I = 1,6 00020430
0164* IF(I(I).EQ.0) GO TO 20 00020440
0165* LOG(I)=.TRUE. 00020450
0166* K=I(L) 00020460
0167* 10 CONTINUE 00020470
0168* RETURN 00020480
0169* END 00020490
B-30
REAL K1,K2,K4(10),K5,K6,K11,K12,NU,II,LOAD,ACCUR(3),ALK(9)

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

REAL K1,K2,K4(10),K5,K6,K11,K12,NU,II,LOAD,ACCUR(3),ALK(9)

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400

COMMON/ASDT/LAYER,NLAYS,M.R,Z,NU(10),ACCUR,LOAD,HOSTRS,NZEROS,H(9)I0020400

COMMON/INDATA/XMAX, AI(9),BI(9),C11(9),D(9),EE(9),F(9),G(9),H1(9),I0020400
DO12(K) = 4.0*NU(J)*K5(J)
C(J2,1,K) = -2.0
E012(K) = K11
F012(K) = E012(K)/2.0
F022(K) = 1.0-4.0*NU(J+1)
FF(2,1,K) = 2.0
G02(K) = K12*(1.0-0.5/K1(J))
H02(K) = K12*(1.0+0.5/K1(J))
DO12(K) = 2.0*K12/K1(J)
G02(K) = K12+1.0/K1(J)

30 CONTINUE
J1 = K
DO 40 K = 1,1

DUMMY = 1.0-AL(K)
Q112(K) = K12*F(X)*H(K)+Q111(K)*K5(K)
Q122(K) = AL(K)*H(K)*(2.0*NU(K+1)-K5(K))
40 CONTINUE

IF(LAYER.EQ.NLAYS) GO TO 50

C-----------------------------------------------------------------------------
C THESE CONSTANTS ARE USED FOR THE ASYMPTOTIC EVALUATION OF THE CHARACTERISTIC
C FUNCTIONS IN MATRIX. C-----------------------------------------------------------------------------

J = LAYER
RK1 = 2.0*NU(J+1)*C(J)
RK2 = 2.0*NU(J+1)*A(J)
RK3 = 2.0*NU(J+1)*D(J)
Z021 = Q011(J)*C(J)
RK4 = Z021*H(J)
K12 = 1.0-A(J)
Z011 = Q011(J)*D(J)
Z111 = AL(J)*(RK3-G(J)-K5(J)*B1(J))
Z112 = Q111(J)*EE(J)+K12*H(J)
Z112 = Q112(J)*RK2+EE(J)+K5(J)*R12*H(J)

50 RETURN
END

SUBROUTINE CONPNT(R,HOSTRS, IOAO,ZN2,L2)

C------------------------------------------------------------------------------
THIS SUBROUTINE DETERMINES FOR EACH POINT THE COMPONENTS OF STRESS, ETC.

FOR POINTS AT THE RIM OF THE LOAD SOME OF SINGULAR BEHAVIOUR, A MESSAGE IS PRINTED.

LOAD CONFIGURATION SEPARATELY.

INTEGRALS NEEDED FOR COMPUTATION OF THE DESIRED COMPONENTS OF STRESS, ETC.

COMPONENTS CANNOT BE CALCULATED BECAUSE OF SINGULAR BEHAVIOUR, A MESSAGE IS PRINTED.

REAL STRESS, EPS, RLOW, N2, L2

LOGICAL IARG(6,12), KARG(6,4), JJ(12,15)

COMMON/STDATA/STRESS(27), EPS(17), RLOW, ST, CT, L, ACC

COMMON/TAPE/NOUT

DATA IARG/

DATA KARG/

DATA JJ/

DATA J/.
1210  30  I=J+5
1211  IF(Z.LT.ACC)  I=I-3
1220  GO TO 50
1221  40  I=J+11
1222  IF(ABS(Z-1.0).LT.ACC)  I=I-3
1223  50  IF(STRESS(4).OR.STRESS(10)) CALL LOGSET(KARG(1,1),EPS)
1224  IF(STRESS(5)) CALL LOGSET(KARG(1,2),EPS)
1225  IF(STRESS(3))  EPS(3)=.TRUE.
1226  IF(STRESS(11)) EPS(4)=.TRUE.
1227  IF(STRESS(12)) CALL LOGSET(KARG(1,3),EPS)
1228  IF(STRESS(6).AND.(Z.GT.ACC)) EPS(1)=.TRUE.
1229  IF(.NOT.STRESS(8)) GO TO 60
1230  IF(Z.LT.ACC) GO TO 60
1231  IF(R.GT.ACC) EPS(5)=.TRUE.
1232  60  DO 90  J=1,12
1233  IF(.NOT.STRESS(J)) GO TO 90
1234  70  ERR = 1
1235  80  I=I-2
1236  90  CONTINUE
1240  9000  FORMAT(* AT THIS POINT SRR, SST, ERR AND EZZ HAVE A LOGARITHMIC SING.)
1271* IULARITY*)
1272* 9010 FORMAT(5 AT THIS POINT SRT AND ERT HAVE A LOGARITHMIC SINGULARITY)
1273* 10)
1274* 9020 FORMAT(5 AT THIS POINT SRT, STR, ERR, EZZ AND ERT HAVE A LOGARITHMIC SINGULARITY)
1275* IMIC SINGULARITY*)
1276* END
1277* SUBROUTINE GENDAT(N,NZEROSR,ACC)
1278* C-----------------------------------------------------------------------
1279* C THIS SUBROUTINE GIVES THE ZEROS OF THE PRODUCTS J0(XR)*J1(X) AND J1(XR)*J1(X) IN
1280* C THE RIGHT ORDER. THE SUBSEQUENT ZEROS ARE STORED IN ZEROS FOR USING THEM IN INTEGRAL.
1281* C THE ZEROS OF JO AND J1 ARE STORED AS BZEROS IN THE BLOCK DATA.
1282* C-------------------------------------------------------------------------
1283* COMMON/GEDATA/BZEROS(149,2),ZEROS(298)
1284* ZFCR.LT.ACC.OR.ABS(R-1.0).LT.ACC) GO TO 40
1285* 1=1
1286* J=1
1287* DO 20 K=1,298
1288* IF(I.GT.149) GO TO 30
1289* IF(J.GT.149) GO TO 130
1290* IF(BZEROS(I,2).LT.BZEROS(J,N+1)/R) GO TO 10
1291* ZEROS(K)=BZEROS(J,N+1)/R
1292* J=J+1
1293* GO TO 20
1294* 10 ZEROS(K)-BZEROS(I,2)
1295* 1=1+1
1296* CONTINUE
1297* NZEROSNZEROS298
1298* RETURN
1299* 20 CONTINUE
1300* NZEROS+K-1
1301* RETURN
1302* DO 60 IF(R.GT.ACC) GO TO 70
1303* 50 DO 60 I=1,149
1304* ZEROS(I)+BZEROS(I,2)
1305* 60 CONTINUE
1306* NZEROS149
1307* RETURN
1308* 70 IF(N.EQ.1) GO TO 50
1309* DO 80 K=1,149
1310* ZEROS(2*K-1)+BZEROS(K,1)
1311* ZEROS(2*K )BZEROS(K,2)
1312* 80 CONTINUE
1313* NZEROS298
1314* RETURN
1315* END
1316* SUBROUTINE ASYMPTER(ACC)
1317* C-----------------------------------------------------------------------
1318* C THIS SUBROUTINE ORGANIZES THE COMPUTATION OF THE ASYMPTOTIC PART OF THE INTEGRALS
1319* C AS USED FOR THE TOP-LAYER ONLY.
1320* C ASYMPT CALLS IN SUBROUTINE ASS
1321* C ASYMPT CALLS IN FUNCTIONS FLLK
1322* C-----------------------------------------------------------------------
1324. C
1325. C ---------------
1326. COMMON/CONST/C,ELLE,ELLK,FLLE,FLLK
1327. C ---------------
1328. RETURN
1329. END

DOUBLE PRECISION

FUNCTION FLLK(KACC2)

C ----------------------------------- ------------------------------------------

B-36
THIS FUNCTION SUBROUTINE EVALUATES THE

COMPLETE ELLIPTIC INTEGRAL OF THE SECOND KIND FROM A SERIES-EXPANSION ACCORDING TO

BYRD AND FRIEDMAN, HANDBOOK OF ELLIPTIC INTEGRALS FOR ENGINEERS AND PHYSICISTS,

FORMULA 900.10 FOR KACC2.LT.0.5

FORMULA 900.07 FOR KACC2.GE.0.5

------------------------------------------------------------------------------

DOUBLE PRECISION KACC2, KACC, KA

IF (KA.LT.0.5D0) GO TO 10

IF (KACC.GT.0.5D0) GO TO 10

KACC = 1.0D0 - KACC2

IF (KACC.LT.1.0D-04) GO TO 20

FLLE = 1.0D0 - KA*(0.250D0*KA*(0.019531250D0 + KA*(0.006729126D0 + KA*(0.004626274D0 + KA*(0.003375291D0 + KA*(0.002925807D0 + KA*(0.002457850D0 + KA*(0.002023490'D0 + KA*(0.0016339685D0 + KA*(0.00134700023850

GO TO 30

FLLE = 2.0D0*FLLE/3.1415926535D0

GO TO 30

RETURN

FUNCTION FLMBDA(DR,C,E,ELLK,ELLE,KACC2)

THIS FUNCTION SUBROUTINE EVALUATES THE

HEUMAN'S-LAMBDA FUNCTION FROM A SERIES-

EXPANSION ACCORDING TO

BYRD AND FRIEDMAN, HANDBOOK OF ELLIPTIC INTEGRALS FOR ENGINEERS AND PHYSICISTS,

FORMULA 904.00

USE IS MADE OF THE COMPLETE ELLIPTIC INTEGRAL

AND ELLE EVALUATED BY FLK AND FLLE.

DOUBLE PRECISION DR,DASIN,SUM.PHI,DAS,DC,A,TA,TAI,KACC2,TWAI,DAR,ELLK

DA(00400

DA(00400

DA(00400

GO TO 30

RETURN

END

FUNCTION FLMBDA(DR,C,E,ELLK,ELLE,KACC2)

RETURN

END
1430 10 DASIN = C/DAR
1431 IF(C.LT.(O.ID-05 DAR)) GO TO 20
1432 PHI = DATAN(DASIN)
1433 GO TO 30
1434 20 PHI = DASIN
1435 30 IF(DABS(PHI-1.570796326000).GT.1.0D-6) GO TO 40
1436 FLMBDA=1.0
1437 GO TO 60
1438 40 DS-OSIN(PHI)
1439 DC-DCOS(PHI)
1440 E - ELLE
1441 K = ELLE
1442 FLMBDA = PHI*E
1443 T=0.500*(PHI-DS*DC)
1444 A=0.500*KACC2
1445 SUM=A*T*(2.000*K-E)
1446 IF(SUM.LT.(O.ID-07) ...
1483*  EC = SNGL(C)  00024440
1484*  IF(R.LT.ACC) GO TO 20  00024450
1485*  EMR = 1.0 - R  00024460
1486*  EPR = 1.0 + R  00024470
1487*  C2 = EC*EC  00024480
1488*  RT2 = C2*EPR*EPR  00024490
1489*  RT = SQRT(RT2)  00024700
1490*  R2 = RR  00024710
1491*  EMRR = 1.0 - R2  00024720
1492*  OR = BLE(R)  00024730
1493*  DEPR = 1.000 + DR  00024750
1494*  DEMR = 1.000 - OR  00024770
1495*  C2 = C*C  00024790
1496*  DRT2 = C2 + DEPR*DEPR  00024800
1497*  ORT = SQRT(DRT2)  00024810
1498*  DR2 = R*R  00024870
1499*  EIIRR = 1.0 - R2  00024840
1500*  DR = ORR  00024880
1501*  DEPR = 1.000 + DR  00024840
1502*  DEMR = 1.000 - OR  00024860
1503*  F101 = 0.500*ELLE*(1.000 - DRC2)/(DAD*DR + ELLK/DR)  00024860
1504*  F110 = DRT*ELLE*(1.000 + DRC2)/(2.000*DR)  00024860
1505*  F111 = C*(ELLE*(1.000 + DRC2)/DAD - ELLK)/(2.000*DR)  00024860
1506*  FIM1 = 0.500*ELLE*DR  00024870
1507*  F100 = -0.500*ELLE*DR  00024880
1508*  F110 = DRT*ELLE*(1.000 + DRC2)/(2.000*DR)  00024860
1509*  F111 = C*(ELLE*(1.000 + DRC2)/DAD - ELLK)/(2.000*DR)  00024860
1510*  F110 = DRT*F110  00024860
1511*  F110 = F110 + 0.500*ELE/DR + ELLK*C*(1.000,DR2 + 0.500*DC2)/(2.000*DRRT)  00024860
1512*  F110 = F110 - F110 + 0.500*ELE/(2.000*DRRT)  00024860
1513*  HIP = R  00024860
1514*  IF(R.GT.1.0) HIP = I.0/R  00024860
1515*  IF(ABSCEMR).LT.ACC) GO TO 10  00024860
1516*  F101 = F101 + 0.500*(SNGL(ELLK)*EMMR/RT + SIGN(EC*AIMBDA.EMR))  00024870
1517*  F100 = F100 + 0.500*SIGN(ALMBDA.EMR)  00024880
1518*  F110 = F110 + 0.500*SIGN(ALMBDA.EMR)  00024890
1519*  F111 = F111 + 0.500*SIGN(ALMBDA.EMR)  00024900
1520*  F100 = F100 - F100  00024910
1521*  F100 = F100 - F100 + 0.500*EC - F100  00024920
1522*  F110 = F110 - F110 - 0.500*EC  00024930
1523*  F110 = F110 - F110 - 0.500*EC  00024940
1524*  GO TO 30  00024950
1525*  F100 = F100 + 0.500  00024960
1526*  F100 = F100 + 0.500  00024970
1527*  F110 = F110 + 0.500  00024980
1528*  F110 = F110 + 0.500  00024990
1529*  GO TO 30  00025000
1530*  AD = 1.0 + ECEC  00025010
1531*  RT = SQRT(AD)  00025020
1532*  ADRT = AD*RT  00025030
1533*  F101 = 1.0/ADRT  00025040
1534*  F110 = 0.5/ADRT  00025050
1535*  F110 = 1.5*EC/(AD*ADRT)  00025060

B-39
SUBROUTINE INTEGRAL(IL, INTV, INT)

C THIS SUBROUTINE CONTROLS THE SIMULTANEOUS COMPUTATION
C OF A GROUP OUT OF THE 17 INTEGRALS.

C IL is the group with J0(XR) Ji(X) INTEGRALS.
C IL+2 is the group with Ji(XR) Ji(X) INTEGRALS.

C INT is the total number of required integrals in the group.
C INTV is the total number of required integrals.

C THE SET OF COMPUTED INTEGRALS IS DELIVERED IN INT.

C ACTUAL INTEGRATION BY MEANS OF A GAUSS-QUADRATURE IS
C PERFORMED BY CALLING QUAD.

C INTEGRATION PROCEEDS BY QUADRATURE OVER INTERVALS FROM
C ONE BESSEL ZERO TO THE NEXT, FROM THE ORIGIN TO THE FIRST
C BESSEL ZERO, USING JACOBI-GAUSS QUADRATURE, OBTAINING
C DESIRED ACCURACY BY SUBSEQUENT RAISING THE ORDER
C STARTING WITH THE 4TH ORDER.

C INTEGRATION STOPS AS SOON AS TWO SUCCESSIVE INTERVALS
C DO NOT CONTRIBUTE SIGNIFICANTLY.

C INTEGRATION STOPS PREMATURELY IF IN THE FIRST INTERVAL
C MORE THAN 30 SUBDIVISIONS ARE NEEDED.

C INTEGRATION STOPS PREMATURELY IF IN THE FOLLOWING INTERVALS
C EVEN THE 15TH ORDER IS NOT ACCURATE ENOUGH.

C EVEN THE 149TH (298TH) INTERVAL DOES NOT CONTRIBUTE.

C GIVE A NON-NEGIGIBLE CONTRIBUTION.

C-------------------------------------------------------------------------

INTEGER ALFA, ORDER, INTV, INTV2, INTV3, KK, BETA
REAL MIDPNT, LOWER, LOAD, NUACCUR, KS, COMP, FIRST, ISECOND, INT(17), RES(10)
COMMON/ASDT/LAYERN, R, Z, NU(10), ACCUR, HOSTRS, NZEROS(9)
COMMON/GDATA/BZEROS, ZEROS(298)
COMMON/TAPE/NOUT

IF(IL.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(IL.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(IL.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF

IF(Il.EQ.2) THEN
  HINT = 10
ELSE
  HINT = 0
END IF
* DO 1000 I = 1, NINT
  * K(K) = 0
  * CONTINUE
  * IF(LAYERS.NE.1) GO TO 2000

* C-----------------------
  * CALCULATION OF THE ASYMPTOTIC PART OF THE INTEGRALS
  * FOR POINTS IN THE TOP LAYER ONLY.

K DO 1190 I = 1, NINT
  K = INTV(I)
  IF(K.EQ.0) GO TO 1190
  GO TO (1010, 1020, 1030, 1040, 1050, 1060, 1070, 1080, 1090, 1100, 1110, 1120, 1130, 1140, 1150, 1160, 1170), K
  INT(K) = FIOO + 2*FIO1
  GO TO 1190
  INT(K) = -2.0*(1.0 - NU(I))*FIOM1 - Z*FIIO
  GO TO 1190
  INT(K) = Z*FIOM1
  GO TO 1190
  INT(K) = FIOO - Z*FIOM1
  GO TO 1190
  IF(R.GE.ACCUR(I)) INT(K) = INT(K)/R
  CONTINUE

* C-----------------------
  * INTEGRATION FROM THE ORIGIN TO THE FIRST BESSEL ZERO.

B-41
1642* 2000 INTT2 = INTT  
1643*       INTT3 = INTT  
1644*       DO 2010 J = 1,MINT  
1645*          INTV2(J) * INTV(J)  
1646*          INTV3(J) = INTV(J)  
1647* 2010 CONTINUE  
1648*       UPPER = ZEROS(J)  
1649*       ALFA = 0  
1650*       BETA = 0  
1651*       IRIS = 0  
1652*       DELTA = 0.5*ZEROS(J)  
1653* 2020 LOWER = UPPER-DELTA  
1654*       IF(LOWER-ACCUR(J)) 2030,2030.2040  
1655*          ALFA = 1  
1656*          LOWER = 0.0  
1657* 2030 MIDL = 0.5*(LOWER+UPPER)  
1658*       IF(MIDL.EQ.J) GO TO 2050  
1659*       IF(MINFIL.NE.0) GO TO 2010  
1660* 2040 DO 2060 J = 1,MINT  
1661*          COMP(J) = RES(J)  
1662* 2050 CONTINUE  
1663* 2060 CONTINUE  
1664*       IRES = 0  
1665* 2070 MIDL = 0.5*(LOWER+UPPER)  
1666*       CALL QUAD(J,INTV3,MIDPNT,UPPER,16,COMP,J,NTFF,14)  
1667*       IF(NTFF.NE.0) GO TO 2031  
1668*       GO TO 2010  
1669* 2080 IF(IRES.EQ.1) GO TO 2050  
1670*       CALL QUAD(7,INTV3,LOWER,16,FIRST,14)  
1671*       IF(FIRST.EQ.0) GO TO 2090  
1672*      IF(BETAS(COMP(J),LT,ACCUR(J)) ELSE GO TO 2030  
1673*      IF(BETAS(COMP(J)-FIRST(J),SECOND(J))/COMP(J),LT,ACCUR(J))  
1674*       IF(FIRST.EQ.0) GO TO 2090  
1675*       GO TO 2090  
1676* 2090 CONTINUE  
1677*       IF(LOWER.GT.CURR(J)) GO TO 2080  
1678*       FITZ = INTT2-1  
1679*       INTV3(J) = 0  
1680* 2090 CONTINUE  
1681*       IF(INITS.EQ.0) GO TO 2100  
1682*       ALFA = 0  
1683*       LOWER = MIDL  
1684*       DELTA = 0.5*DELTA  
1685*       BETA = BETA+1  
1686*       IF(BETA.GT.JO) GO TO 2150  
1687* C---------------  
1688* C ARRIVAL HERE MEANS THAT THE INTEGRAND IS TOO  
1689* C IRREGULAR TO GET INTEGRATED OVER THE REGION  
1690* C THE ORIGIN TO THE FIRST BISEX ZERO.  
1691* C---------------  
1692*       IRES = 1  
1693*       DO 2100 J = 1,MINT  
1694*          COMP(J) = SECOND(J)  
1695* 2100 CONTINUE  
1696*
1695* RES(J) = FIRST(J) 00026460
1696* 00026470
1697* CONTINUE 00026480
1698* GO TO 2070 00026490
1699* 00026500
1700* K = INTV2(J) 00026510
1701* IF(K.EQ.0) GO TO 2120 00026520
1702* INT(K) = INT(K)+FIRST(J)+SECOND(J) 00026530
1703* IF(INTV3(J).NE.0) GO TO 2120 00026540
1704* INTV2(J) = 0 00026550
1705* CONTINUE 00026560
1706* 00026570
1707* "UPPER = LOWER" 00026580
1708* "INTT3 = INTT2" 00026590
1709* 00026600
1710* IF(ALFA) 3000,2140,2130 00026610
1711* 2130 DELTA*2.0 00026620
1712* 00026630
1713* BETA = BETA-1 00026640
1714* 2140 ALFA = ALFA+1 00026650
1715* GO TO 2020 00026660
1716* 00026670
1717* 00026680
1718* 3000 IFIN = NZEROS-1 00026690
1719* DO 3010 J = 1,NINT 00027000
1720* 00027010
1721* INTV2(J) = INTV(J) 00027020
1722* 00027030
1723* DO 3020 J = 1,NINT 00027040
1724* 00027050
1725* INTV3(J) = INTV2(J) 00027060
1726* 00027070
1727* 3020 CONTINUE 00027080
1728* 00027090
1729* INTT2 = INTT2 00027100
1730* 00027110
1731* CALL QUAD(IL,INTV3,ZEROS(IBESS),ZERGS(IBESS+1),ORDER,SECOND, 00027120
1732* 1 NTELL(I), I NTELL(0) 00027130
1733* DO 3040 J = 1,NINT 00027140
1734* 00027150
1735* IF(K.EQ.0) GO TO 3040 00027160
1736* IF(ABS(INTV2(J)).LT.0.01) GO TO 3030 00027170
1737* IF(ABS(INTV3(J)-SECOND(J))/ABS(FIRST(J)).LT.0.1*ACCUR(3)) 00027180
1738* 1 GO TO 3040 00027190
1739* GO TO 3050 00027200
1740* 00027210
1741* 3030 IF(ABS(FIRST(J)-SECOND(J)).GE.0.1*ACCUR(2)) GO TO 3050 00027220
1742* 3040 INTV3(J) = 0 00027230
1743* 3050 CONTINUE 00027240
1744* 00027250
1745* IF(INTT3.EQ.0) GO TO 3080 00027260
1746* 3070 CONTINUE 00027270
1747* 3080 CONTINUE 00027280
1748* WRITE(NOUT,9020) 00027290
1749* WRITE(NOUT,9050) ZEROS(1855) 00027300
1750* ARRIVAL HERE MEANS THAT THE DESIRED ACCURACY CANNOT 00027320
1751* BE MET BY MEANS OF THE AVAILABLE GAUSS-JACOBI 00027330
1752* POLYNOMIALS. 00027340
1753* GO TO 3180 00027350
1754* DO 3120 J = 1,NINT 00027360
1755* K = INTV(J) 00027370
1756* IF(K.EQ.0) GO TO 3120 00027380
1757* INT(K) = INT(K)+SECOND(J) 00027390
1758* IF(ABS(INT(K)).LT.0.01) GO TO 3090 00027400
1759* IF(ABS(SECOND(J)).LT.0.1*ACCUR(3)) GO TO 3110 00027410
1760* GO TO 3100 00027420
1761* IF(ABS(SECOND(J)).LT.0.1*ACCUR(2)) GO TO 3110 00027430
1762* GO TO 3100 00027440
1763* IF(ABS(SECOND(J)).LT.0.1*ACCUR(3)) GO TO 3110 00027450
1764* IF(ABS(SECOND(J)).LT.0.1*ACCUR(2)) GO TO 3110 00027460
1765* IF(ABS(SECOND(J)).LT.0.1*ACCUR(3)) GO TO 3110 00027470
1766* IF(ABS(SECOND(J)).LT.0.1*ACCUR(2)) GO TO 3110 00027480
1767* IF(ABS(SECOND(J)).LT.0.1*ACCUR(3)) GO TO 3110 00027490
1768* IF(ABS(SECOND(J)).LT.0.1*ACCUR(2)) GO TO 3110 00027500
1769* IF(ABS(SECOND(J)).LT.0.1*ACCUR(3)) GO TO 3110 00027510
1770* CONTINUE 00027520
1771* IF(INTT.EQ.0) GO TO 3140 00027530
1772* CONTINUE 00027540
1773* WRITE(NOUT,9030) 00027550
1774* WRITE(NOUT,9050) ZEROS(IFIN) 00027560
1775* ARRIVAL HERE MEANS THAT ALL AVAILABLE BESSEL ZEROS 00027570
1776* HAVE BEEN EXHAUSTED BECAUSE OF ILL CONVERGENCE OF 00027580
1777* THE INTEGRALS. 00027590
1778* RETURN 00027600
1779* DO 3180 J = 1,NINT 00027610
1780* K = INTV(J) 00027620
1781* IF(K.EQ.0) GO TO 3170 00027630
1782* IF(K.SLE.0) 3150,3150,3160 00027640
1783* 3150 INT(K) = INT(K)*LOAD 00027650
1784* 3160 INT(K) = INT(K)*HOSTRS 00027660
1785* CONTINUE 00027670
1786* GO TO 3170 00027680
1787* INT(K) = INT(K)*HOSTRS 00027690
1788* CONTINUE 00027700
1789* RETURN 00027710
1790* WRITE(NOUT,9010) (INTV(J),J=1,NINT) 00027720
1791* RETURN 00027730
1792* RETURN 00027740
1793* RETURN 00027750
1794* RETURN 00027760
1795* RETURN 00027770
1796* RETURN 00027780
1797* END 00027790
1798* SUBROUTINE QUAD (IL,INTV3,ALO,UP,NGAUSSFSC,NTELL) 00027800
1799* THIS SUBROUTINE CALCULATES FOR THE SET 00027810

B-44
INTV THE INTEGRALS OF THE CORRESPONDING AND UP BY USING A GAUSS QUADRATURE OF ORDER NGAUSS. FOR NGAUSS=16 A LEGENDRE-GAUSS QUADRATURE. RE OF ORDER 8. FOR NGAUSS.LT.16 A JACOBI-GAUSSQUADRATURE. THE ABSCISSAE AND WEIGHTS OF BOTH ARE STORED AS AGAUS AND HGAUS IN THE BLOCK DATA. THE SET OF INTEGRANDS IS COMPUTED DURING SUBSEQUENT CALLING IN OF SUBROUTINES MATRIX AND FUNCTION IGRAND THE SET OF RESULTING INTEGRALS IS DELIVERED IN FSC

```fortran
INTEGER INTV(10)
REAL IGRANDFSC(10)
COMMON/GAUSS/AGAUSS(16,16),HGAUSS(16,16)
NINT = 7
IF(IL.EQ.2) NINT = 10
DO 10 J = 1, NINT
   K = INTV(J)
   IF(K.EQ.0) GO TO 10
   FSC(J) = 0.0
10 CONTINUE
LABEL = 0
IF(IL.EQ.2) GO TO 20
DO 20 J = 1, NINT
   K = INTV(J)
   IF(K.EQ.0) GO TO 20
   FSC(J) = FSC(J) + HGAUSS(I,NGAUSS)*IGRAND(F1*AGAUSS(I,NGAUSS)+F2)
20 CONTINUE
```
1854* DD 60 J = 1,NINT
1855* K = INT(V(J))
1856* IF(K.EQ.0) GO TO 60
1857* FSC(J) = FSC(J)*F
1858* CONTINUE
1859* 70 RETURN
1860* END
1861* SUBROUTINE MATRIX (X,LABL,NTEL)
1862* C------------------------------------------------------------------------------
1863* C THIS SUBROUTINE COMPUTES THE SET OF CHARACTERISTIC-FUNCTIONS TO,VO,SO,UO,TI,VI,
1864* C FOR THE VALUE OF THE INTEGRATION-PARAMETER.
1865* C THEY WERE STORED IN COMMON/INDATA/.
1866* C CHARACTERISTIC-FUNCTION VALUES ARE DELIVERED IN COMMON/IGRAN/.
1867* C LABEL DETERMINES WHICH CHARACTERISTIC-FUNCTIONS ARE NEEDED:
1868* C -LABEL=1*T0,V0,S0,U0
1869* C -LABEL=2: TI,VI,S1,U1
1870* C -LABEL=3:*TO,V0,S0,U0,T1,VI,S1,U1
1871* C -LABEL=4:*TQ1,SQ1
1872* C -LABEL=5:*T0,V0,S0,U0,TQ1,SQ1
1873* C -LABEL=7:*T0,V0,S0,U0,T1,VI,S1,U1,TQ1,SQ1
1874* C SUBROUTINE IS INTERRUPTED AND RETURNED WITH NTELL=1 WHEN SOLUTION BECOMES TOO INACCURATE BECAUSE OF ILL MATRIX-CONDITION DURING INVERSION.
1875* C------------------------------------------------------------------------------
1876* REAL LOADNU,J,W(4,4),P(4,2),PP(2,2),K1,K2,K5,K6,NJ(2,2,9),KK6,0002866)
1877* IACCUR(3),NP(2,10),NJ2(9),P3(2),NP2(10),K6(10)
1878* COMMON/ASOT/LAYER,NLAYS,M,RZW(I),ACCUR,LOAD,HOSTS,NZEROS,H19)00028670
1879* K5(10),E(10),AL(9),THICK(9),RADIUS(10)
1880* COMMON/INDATA/XMAX, A1(9),B1(9),C1(9),D(9),E(9),F(9),G(9),H(9),N1(9)
1881* 100(9)
1882* COMMON/INDATA/XMAX, 111(9),K1(9),K2(9),K6(10),BE(9),BU(9),BMU(9),B2U(9),B2UU(9),0002880
1883* 2J2(9),J1(210),G32(10),G012(9),G022(9),G122(9),0002881
1884* 3H02(9),H022(9),H122(9),D022(9),D112(9),C012(9),C021(9),E012(9),0002882
1885* 4F012(9),F112(9),F022(9),CC(4,2,9),DD(2,2,9),FF(2,2,9),GG(2,2,10),0002883
1886* L01(9)
1887* COMMON/INDATA/XMAX, 5SF(2,10),RK(4,2,10),DD(2,9),G02(9),G12(9),G222(9),0002884
1888* 6DF22(9),L01(9),G012(9),G022(9),G122(9),0002885
1889* 7QF0(9),QF1(9),Z011,Z111,Z121,Z122,Z211,Z212,Z213,Z212,Z212,Z212,Z212,Z212,0002886
1880* 8Z122,Z222,K4
1881* COMMON/ILL/I0,V0,SO,U0,T1,VI,S1,U1,TQ1,SQ1,FPIGR,EX1,EX2
1882* COMMON/TAPE/NOUT
1883* COMMON/GEN/TAPE/NOUT
1884* COMMON/GEN/TAPE/NOUT
1885* COMMON/GEN/TAPE/NOUT
1886* COMMON/GEN/TAPE/NOUT
1887* COMMON/GEN/TAPE/NOUT
1888* COMMON/GEN/TAPE/NOUT
1889* COMMON/GEN/TAPE/NOUT
1890* COMMON/GEN/TAPE/NOUT
1891* COMMON/GEN/TAPE/NOUT
1892* COMMON/GEN/TAPE/NOUT
1893* COMMON/GEN/TAPE/NOUT
1894* COMMON/GEN/TAPE/NOUT
1895* COMMON/GEN/TAPE/NOUT
1896* COMMON/GEN/TAPE/NOUT
1897* COMMON/GEN/TAPE/NOUT
1898* COMMON/GEN/TAPE/NOUT
1899* COMMON/GEN/TAPE/NOUT
1900* COMMON/GEN/TAPE/NOUT
1901* COMMON/GEN/TAPE/NOUT
1902* COMMON/GEN/TAPE/NOUT
1903* COMMON/GEN/TAPE/NOUT
1904* COMMON/GEN/TAPE/NOUT
1905* COMMON/GEN/TAPE/NOUT
1906* COMMON/GEN/TAPE/NOUT

B-46
1907*  TQI = 1.0  
1908*  IF(LAYER.EQ.1) GO TO 30  
1909*  J = LAYER-1  
1910*  DO 20  K = 1,J  
1911*  TQI=TQI*2.0*(I.O-AL(K))/((I.O-AL(K))*(I.O+KI(K))+0.5*AL(K)*X)  
1912*  20  CONTINUE  
1913*  SQI=TQI*(0.5*AL(LAYER)*X-(1.0-AL(LAYER))*K2(LAYER))/((I.O-AL(LAYER))*X)  
1914*  30  CONTINUE  
1915*  LABEL = LABEL-4  
1916*  C CALCULATION OF TQI AND SQI FOR X.LT.XMAX  
1917*  C-- ----------------------------------------------------------------------  
1918*  100 IF(J1.EQ.0) GO TO 120  
1919*  DO 110  J = 1,J1  
1920*  GG2(J+I) = G20(J)-G21(J)*X  
1921*  H2fJ+I) = H20(J)+G21(J)*X  
1922*  110  CONTINUE  
1923*  120  DO 150  K = 1,M  
1924*  IF(J1.EQ.0) GO TO 140  
1925*  DO 130  I = 1,J1  
1926*  IF(J2(I).EQ.K) GO TO 150  
1927*  130  CONTINUE  
1928*  DO 150   
1929*  W = 0.5*(1.0+KI(K))  
1930*  W2 =-0.5*K2(K)  
1931*  NJ(1,1,K) = W +W3  
1932*  NJ(1,2,K) = W2-W3  
1933*  NJ(2,1,K) = W2+W3  
1934*  NJ(2,2,K) = W1-W3  
1935*  150  CONTINUE  
1936*  J5 = J1+1  
1937*  DO 300  MM = 1,J5  
1938*  N = J5+1-MM  
1939*  IF(N-1) 160,160,170  
1940*  GO TO 180  
1941*  160  J3 = 1  
1942*  GO TO 180  
1943*  170  J3 = J2(N-1)+1  
1944*  180  IF(J3(N) 190,190,200  
1945*  190  J4 = M  
1946*  GO TO 210  
1947*  200  J4 = J2(N)-1  
1948*  210  IF(J3.GT.J4) GO TO 240  
1949*  DO 230  J1 = J3,J4  
1950*  EXPI=EXP(EXPO)*SS(I,IL)  
1951*  230  EXPI=0.0  
1952*  240  DO 220  I-1,2  
1953*  SS(I,IK) = N11,1IK+EXPI*N11,2,IK+SS(2,IL)
1960* 230 CONTINUE
1961* 240 NN = N-1
1962* EXP0 = X*T2(J3)
1963* IF(EXPO.LT.-70.0)GO TO 242
1964* EXP2 = EXP(EXPO)
1965* GO TO 244
1966* 242 EXP2=0.0
1967* 244 PROD=G02(N)*SS(1,J3)*EXP2
1968* P2 = PROD+HH2(N)*SS(2,J3)
1969* CONTINUE
1970* TEST MATRIX-CONDITION BEFORE INVERSION.
1971* IF(ABS(P2).LT.1.0E-7*ABS(PROD)/ACCUR(3)) GO TO 2000
1972* IFABS(P2).LT.1.0E-7*ABS(PROD)/ACCUR(3)) GO TO 2000
1973* PP2 = 1.0/P2
1974* IF(N.EQ.1) GO TO 310
1975* DO 350 I = 1,2
1976* 350 X2 = X*X
1977* 360 DO 380 I = 1,J
1978* 380 NP2(I+1) = NP2(I) + NP2(J3)*X2*ZII
1979* 390 J = J+1
1980* IF(LAYER.GT.J2(J)) GO TO 360
1981* SQI = SS(1,J)*NP2(J5)
1982* TQI = SS(2,J)*NP2(J5)
1983* LABEL = LABEL-4
1984* ASYMPOTIC EVALUATION OF T0, V0, S0, U0, T1, VI, SI AND U1 FOR X.GE.XMAX.
1985* IF(LABEL.EQ.0) RETURN
1986* IF(X.LT.XAX) GO TO 1100
1987* L = LAYER
1988* X2 = X*X
1989* X3 = X2*X
IF(LABEL.GT.1) GO TO 1030
00029940

IF(LABEL.EQ.0) RETURN
00029950

NP(1,1) = 2.0+NU(1)
00029960

NP(2,1) = -1.0
00029970

GO TO 1040
00029980

NP(2,1) = 1.0
00030000

POF = 1.0
00030010

IF(L.EQ.1) GO TO 1060
00030020

DO 1050 K = 2,L
00030030

J = K-1
00030040

POF = POF*K6(J)/(QFO(J)+QF1(J)*X)
00030050

WI = -AL(J)*X
00030060

W9 = H(J)*X
00030070

NP(1,K) = NP(1,J)*(QOII(J)+Ql11(J)*X+W1*W9)+NP(2,J)*(QO12(J)
00030080

+QI12(J)*X+Q212(J)*X2+W1*W9*W9)
00030090

NP(2,K) = -W1*NP(1,J)+NP(2,J)*(QO22(J)+QI22(J)*X-W1*W9)
00030100

I(L.NE.NLAYS) GO 10
00030110

S = 0.0
00030120

U = 0.0
00030130

GO TO 1070
00030140

S = (NP(1,L)*ZII+NP(2,L)*ZI2)*PQF/(QFO(L)+QFI(L)*X) 00030150

I(J) = (NP(1,L)*ZI+NP(2,L)*Z22)*PQF/(QFO(L)+QF1(L)*X)
00030160

S = (NP(1,J)*ZII+NP(2,J)*ZI2)*PQF/(QFO(J)+QFI(J)*X) 00030170

U = NP(1,J)*PQF
00030180

V = NP(2,J)*PQF
00030190

IF(LABEL.GT.1) GO TO 1080
00030200

TO = T
00030210

VO = V
00030220

VI = V
00030230

S0 = S0
00030240

U0 = U0
00030250

TO = T
00030260

VO = V
00030270

VI = V
00030280

LABEL = LABEL-2
00030290

GO TO 1020
00030300

C ------------------------------------------------------------------------ 00030310

C CALCULATION OF TO,VO,S0,U0,TI,VI,SI AND 00030320

C U1 FOR X.LT.XMAX. 00030330

C------------------------------------------------------------------------ 00030340

IF(JI.EQ.0) GO TO 1120
00030350

DO 1110 J = 1,JI
00030360

K = J2(J)
00030370

WI = -AL(K)*X
00030380

W9 = H(K)*X
00030390

CC(1,1,J) = COII(J)+2.0*W9
00030400

CC(1,2,1) = CO12(J)+2.0*W9*W9
00030410

CC(2,7,2) = COII(J)-2.0*W9
00030420

DD(1,2,1) = D012(J)+D011(J,1)*W9
00030430

DD(2,2,1) = D022(J)+D021(J,1)*W9
00030440

FF(1,1,J) = -COII(J)-2.0-W9
00030450

FF(1,2,1) = F012(J)+F112(J)*W9-2.0*W9*W9
00030460
2066* FF(2,2,J) = FO22(J)+2.0*M9 00030470
2067* GG(1,2,J+1) = GO12(J)+GO(1,1,J+1)*M9 00030480
2068* GG(2,1,J) = GO21(J)+M9 00030490
2069* GG(2,2,J+1) = GO22(J)+GO21(J)*H(J)*M1+M9 00030500
2070* HH(1,2,J+1) = HO12(J)+HH(1,1,J+1)*M9 00030510
2071* HH(2,1,J+1) = HO21(J)+M9 00030520
2072* HH(2,2,J+1) = HO22(J)+HO21(J)*M9+H122(J)+M9 00030530
2073* 1110 CONTINUE 00030540
2074* 1120 DO 1150 I=1,M 00030550
2075* IF(J1.EQ.0) GO TO 1140 00030560
2076* DO 1130 I = 1,J1 00030570
2077* IF(J2(I).EQ.K) GO TO 1150 00030580
2078* 1130 CONTINUE 00030590
2079* 1140 W1 = BMU(K)*X 00030600
2080* W9 = H(K)*X 00030610
2081* W10 = W9*X 00030620
2082* W2 = W10*BE(K) 00030630
2083* W1 = W2*M9 00030640
2084* W3 = W9+C(K) 00030650
2085* W4 = BE(K)*X 00030660
2086* W5 = BU(K)*X 00030670
2087* W8 = BUU(K)*X 00030680
2088* W7 = C1(K)*M9+M9 00030690
2089* W1(1,1,K) = A1(K)+W1-W2 00030700
2090* W1(1,2,K) = -EE(K)+F(K)+W9+M8+BUU(K)*M10-M11 00030710
2091* W1(1,3,K) = D(K)-W3+W1-W2 00030720
2092* W1(1,4,K) = -G(K)+H1(K)*M9-BUU(K)*X-M7+BUU(K)*M10-M11 00030730
2093* W2(1,1,K) = W4 00030740
2094* W2(2,2,K) = B1(K)*M5+W2 00030750
2095* W2(2,3,K) = C1(K)*W4 00030760
2096* W2(2,4,K) = E(K)+M3-W5+W2 00030770
2097* W2(3,1,K) = D(K)+W3-W1-W2 00030780
2098* W2(3,2,K) = G(K)+H1(K)*M9+W8+M7-BUU(K)*M10-M11 00030790
2099* W2(3,3,K) = A1(K)-W1-W2 00030800
2100* W2(3,4,K) = E(K)+F(K)+M9+W8-BUU(K)*M10-M11 00030810
2101* W4(1,1,K) = -C1(K)+W4 00030820
2102* W4(2,1,K) = I1(K)+W3+W5+W2 00030830
2103* W4(3,1,K) = W4 00030840
2104* W4(4,1,K) = B1(K)-W5+W2 00030850
2105* 1150 CONTINUE 00030860
2106* J5 = J1+1 00030870
2107* PKN = 1.0 00030880
2108* DO 1300 MM = 1,J5 00030890
2109* KK6 = 1.0 00030900
2110* M = J5+1-MM 00030910
2111* IF(N-I) 1160,1160,1170 00030920
2112* 1160 J3 = 1 00030930
2113* GO TO 1180 00030940
2114* 1170 J3 = J2(N-I)+1 00030950
2115* 1180 IF(J5-M) 1190,1190,1200 00030960
2116* 1190 J4 = M 00030970
2117* GO TO 1210 00030980
2118* 1200 J4 = J2(N)-1 00030990
IF(J3.GT.J4)
Ga TO 1240
00031000

DO 1230 IJ = J3.J4
00031010

J = J4+J3-13
00031020

IL = JX+1
00031030

KK6 = KK6*K6(IK)
00031040

IF(IN.EQ.LAYER) PKK6 = KK6
00031050

EXP6 = X*12(1L)
00031060

IF(EXP6.LT.-70.0)GO TO 1212
00031070

I = I + J3.IJ
00031080

IF(EXP6.LT.-70.0)GO TO 1212
00031090

I = I + J3.IJ
00031100

DO 1220 K = 1,2
00031110

RR(1.K.IK)=(W(I,1.IK)*RR(1.K.IL)+W(I.2.IK)*RR(2.K.IL))
00031120

1 = EXP1+W(1,3.1K)+RR(3.K.IL)+W(1,4.1K)*RR(4.K.IL)
00031130

CONTINUE
00031140

N = N-1
00031150

GO TO 1244
00031160

EXPO = X*12(3)
00031170

IF(EXPO.LT.-70.0)GO TO 1242
00031180

EXP2 = EXP(EXPO)
00031190

DO 1250 I = 1,2
00031200

00031210

00031220

OPEO = P11,2)*P(2,1)
00031230

DET = PROD-P(1,2)*P(2,1)
00031240

C--------------------------------------------------------------------------------------
00031250

C TEST MATRIX CONDITION BEFORE INVERSION. 00031260

IF(ABS(DE1).LT.1.E-7*ABS(PROD)/ACCUR(3)) GO TO 2000
00031270

QK6 = OT00031280

PP(I,1) = P11,2)*QK6
00031290

PP(2,1) = P(P12,2)*QK6
00031300

PP(2,2) = P(1,1)*QK6
00031310

IF(N.EQ.1) GO TO 1310
00031320

DO 1260 K = 1,2
00031330

NJ1(I,K,NN)=PP(1,1)*DD(I,K,NN)+PP(1,2)*DD(2,K,NN)
00031340

DO 1270 I = 1,4
00031350

DO 1280 I = 1,2
00031360

PP(1,1)+PP(1,2)*EXP2+FF(1,1,NN)*P(1,1)+P(2,1)*EXP2+FF(1,2,NN)*P(2,1)
00031370

PP(2,1) = P(1,1)*QK6
00031380

DO 1290 I = 1,2
00031390

DO 1300 I = 1,2
00031400

RR(1.K,J3-1) = CC(I,K,NN)+PP(I.K)
00031410

RR(3,1.J3-1) = 1.0
00031420

RR(3,2.J3-1) = 0.0
00031430

B-51
C---------------------------------------------------------------------
C ARRIVAL HERE MEANS THAT SOLUTION OF THE
C CHARACTERISTIC FUNCTIONS HAS BEEN STOPPED
C PREMATURELY BECAUSE OF ILL MATRIX CONDI-
C TION MET DURING SOLUTION PROCESS.
C---------------------------------------------------------------------
2218* C
2219* 2000 WRITE(NOUT,9000)X
2220* NTLL = 1
2221* RETURN
2222* 9000 FORMAT(9000,9000)X
2223* END
2224* SUBROUTINE FPIGRA (IL,X)
THIS SUBROUTINE COMPUTES THE BESSEL FUNCTION PART OF THE INTEGRANDS FOR THE INTEGRALS COMPUTED IN INTEGRAL. FOR \( IL=1 \) THIS PART IS \( \text{J}_0(\pi R) \cdot \text{J}_1(\xi) \) FOR \( IL=2 \) THIS PART IS \( \text{J}_1(\pi R) \cdot \text{J}_0(\xi) \).

COMPUTED RESULTS ARE DELIVERED AS FPISR, EXPI AND EXP2 IN COMMON/IGRAN/

THE SUBROUTINE CALLS IN FUNCTION BESS.

REAL LOAD, NU, ACCUR(3), K5

COMMON/ASD1/LAYER, NLAYS, M, R, Z, NU(10), ACCUR, LOAD, HOSTS, NZEROS, M(10)

COMMON/IGRAN/T0, VO, SO, UO, T1, V1, S1, U1, TQ1, S Q1, FPISR, EXPI, EXP2

IF (R .LT. ACCUR(1)) GO TO 40

IF (IL .EQ. 2) GO TO 50

FPISR = \( \text{BESS}(0, \pi R) \cdot \text{BESS}(1, \xi) / \xi \)

GO TO 60

IF (IL .EQ. 2) GO TO 70

FPISR = \( \text{BESS}(1, \pi R) \cdot \text{BESS}(1, \xi) / \xi \)

GO TO 60

IF (IL .EQ. 2) GO TO 80

FPISR = \( 0.5 \cdot \text{BESS}(1, \xi) \)

GO TO 60

IF (FINLAYS .EQ. LAYER) GO TO 70

IF (ABS(\( \pi R \)) .LT. Z) GO TO 80

IF (\( \pi R \)) .LT. Z) GO TO 90

EXPI = \( \exp(-X \cdot Z) \)

GO TO 100

FUNCTION BESS(N, X)

THE BESSEL FUNCTIONS \( \text{J}_0(\xi) \) AND \( \text{J}_1(\xi) \) ARE EVALUATED FROM THEIR CHEBYSHEV SERIES (SEE CLENSHAW, MATH. TABLES—VOL. 5, CHEBYSHEV SERIES FOR MATH. FUNCTIONS)

NPL–DSIR).

THIS PROGRAM SELECTS THE APPROPRIATE CHEBYSHEV CONSTANTS ACCORDING TO WHETHER
DOUBLE PRECISION B(12,2),BP(5,2),BQ(5,2),Z

DATA B /-.3D-8,.76D-7,-.1762D-5,.32460D-4,-.460626D-3,.481918OD-2,0...
1-.34893769D-1,.158067102D+0,-.370094994D0+,.265178613D+0, 0...
2-.87234420-2,.315455943D+0,-.8.29D-7,-.762D-6,. 158870-4, 0...
3-.260444D-3,.3240270D-2,-.29175525D-1,.177709117D+0,-.661443934D+00032670
4.1.28799410DO,-1.19180116D+0,1.29671754D+0/ 00032680
DATA BP/.2D-8,-.52D-7,.3075D-5,-.536522D-3,I.99892070D0+, 00032700
1-.2D-8 .620-7,-.39870-5,.8989900-3,2.00180608D+0/ 00032710
DATA BQ/-.ID-8,.18D-7,-.741D-6,.68385D-4,-.31111709D-1, 00032720
M = N+1
IF(X<8.O) 1,1,2
Z = X*X-0.0625-2.0
BESS = CHEB(B(I,M).12,Z)
IF(N.EQ.1) BESS = 0.125*X*BESS
RETURN
Z = 256.0/(X*X)-2.0
XI = X-0.78539816
IF(N.EQ.1) XI = XI-1.5707963
BESS = (0.79788456/SQRT(X))-(CHEB(BP(N+1,M),5,Z)*COS(XI)-8.O*
1 CHEB(BQ(N+1,M),5,Z)*SIN(XI)/X))
RETURN
FUNCTION CHEB(A,M,Z)
DOUBLE PRECISION A(1),B(14),Z
...
DO 2 I = 1,N
...
CHEB = 0.5DD*(B(N+2)-B(N))
RETURN
END
FUNCTION IGRADE(X,LABEL)
REAL LOAD,NU,ACCUR(3),K5
COMMON/ASDT/LAYERNLAYS.M.RZ.NU(10),ACCUR,LOAD,HOITRS.NZEROS,H(9)00033100
COMMON/IGRAN/.
VOLUME 5 PAGE 9).
RETURN
END
FUNCTION CHEB(A,M,Z)
SUBROUTINE CALC( INT, V, R, RI, RDI, FT, IOAD, HOSTR, PSIO, Z)

COMMON /IGRAND/T0, VO, SB, U0, V1, S1, U1, TQ1, SQ1, FPIGR, EXP1, EXP2

GO TO (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170)

REAL INT(120), V(15), MU
INTEGER FM(19), FMT(5), J(12)

2331 COMMON IGRAND/T0, VO, SB, U0, V1, S1, U1, TQ1, SQ1, FPIGR, EXP1, EXP2

2332 GO TO (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170)

2333 I, LABEL

2334 10 IGRAND = FPIGR * X * ((U0 * (K5(LAYER) - X * Z) - S0) * EXP1 + (T0 + VO * (K5(LAYER) + X) * EXP2)

2335 RETURN

2336 20 IGRAND = FPIGR * X * (U0 * EXP1 + VO * EXP2)

2337 RETURN

2338 30 IGRAND = FPIGR * X * ((S0 * U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2339 RETURN

2340 40 IGRAND = FPIGR * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2341 RETURN

2342 50 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2343 RETURN

2344 60 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2345 RETURN

2346 70 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2347 RETURN

2348 80 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2349 RETURN

2350 90 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2351 RETURN

2352 100 IGRAND = FPIGR * X * ((S0 + U0 * (1.0 + X * Z)) * EXP1 + (V1 * (1.0 - X * Z) - T1) * EXP2)

2353 RETURN

2354 END

COMPONENTS
OF
THE
STRESSES,
STRAINS
AND
THIS
SUBROUTINE
COMPUTES
THE
CYLINDRICAL
DISPLACEMENTS
FROM
THE
17
INTEGRALS
STO-
RED
IN
INT.
THOSE
CALCULATED
COMPONENTS
ARE
STORED
IN
V
AND
OUTPUTTED.

REAL INT(17), V(15), MU, LOAD(16)

INTEGER FM(19), FMT(5), T(12)

B-55
2384* LOGICAL STRESS,EPS,LOW
2385* COMMON/STRDTA/STRESS(27),EPS(17),LOW,ST,CT,L,ACC
2386* COMMON/TAPE/HOUT
2387* DATA FM(1).FM(19),T*
2388* +('IX','E12','4.1','OX','12X','1','X')*,
2389* + 'DISP','LAGE','MENT','S*','
2390* + 'S','TRES','SET ',
2391* + 'R','TRAI','NS ',
2392* DO 10 I=1,15
2393* 10 V(I)=0.0
2394* IF(STRESS( 4).OR.STRESS( 5).OR.STRESS( 7).OR.STRESS(10).OR.
2395* + STRESS(11)).AND.(.NOT.RLOW) FCT=12.0*INT(12)-INT(7)-2.0*INT(14)
2396* IF(.NOT.STRESS( 1)) GO TO 20
2397* V(1)=FT*RADI*CT*(2.0*INT(17)+INT(12)-INT(7))
2398* IF(RLOW) GO TO 20
2399* V(1)=V(1)-FT*R*RADI*INT(3)
2400* IF(STRESS( 2)) V(2)=FT*RADI*ST*(2.0*(INT(17)-INT(14))+INT(12))
2401* IF(.NOT.STRESS( 3)) GO TO 30
2402* V( 3)=CT*(INT(8)+2.0*MU*INT(9))+INT(1)+INYI 4)-2.0*INT(2)
2403* IF(RLOW) GO TO 30
2404* V( 4)=V( 4)-CT*FCT
2405* 30 IF(.NOT.STRESS( 4)) GO TO 40
2406* W( 5)=CT*2.0*MU*INT(9)-2.0*MU*INT(2)-INT(4)
2407* IF(RLOW) GO TO 30
2408* V( 5)=V( 5)+CT*FCT
2409* IF(.NOT.STRESS( 7)) GO TO 50
2410* V( 7)=ST*INT(15)
2411* IF(RLOW) GO TO 50
2412* IF(ISUB(12)) V(12)=ST*(INT(2)-2.0*MU*INT(2)-INT(4))
2413* IF(.NOT.STRESS( 6)) GO TO 90
2414* V( 6)=CT*(INT(8)-2.0*MU*INT(2)-INT(4))
2415* IF(.NOT.STRESS( 8)) GO TO 90
2416* V( 8)=CT*(INT(11)+INT(10)-INT(6))
2417* IF(.NOT.STRESS( 9)) GO TO 110
2418* IF(.NOT.STRESS(11)) GO TO 80
2419* IF(ISUB(12)) V(12)=CT*(INT(2)-2.0*MU*INT(2)-INT(4))
2420* IF(.NOT.STRESS( 6)) GO TO 90
2421* IF(ISUB(8)) V( 8)=CT*(INT(11)+INT(10)-INT(6))
2422* IF(.NOT.STRESS( 9)) GO TO 110
2423* V( 9)=ST*(INT(14)+INT(13)+INT(10))
2424* IF(.NOT.STRESS(11)) GO TO 80
2425* V(10)=CT*(INT(8)-2.0*MU*INT(2)-INT(4))
2426* IF(.NOT.STRESS( 6)) GO TO 90
2427* IF(ISUB(12)) V(12)=CT*(INT(2)-2.0*MU*INT(2)-INT(4))
2428* IF(.NOT.STRESS( 6)) GO TO 90
2429* IF(ISUB(8)) V( 8)=CT*(INT(11)+INT(10)-INT(6))
2430* IF(.NOT.STRESS( 9)) GO TO 110
2431* IF(ISUB(11)) V(11)=CT*(INT(8)-2.0*MU*INT(2)-INT(4))
2432* IF(.NOT.STRESS(11)) GO TO 80
2433* V(11)=CT*(INT(8)-2.0*MU*INT(2)-INT(4))
2434* IF(ISUB(12)) V(12)=ST*(INT(6)-INT(4))
2435* IF(ISUB( 6)) V( 6)=LOAD
2436* IF(ISUB( 8)) V( 8)=HOSTRS*COS(PSSI0)
2437* B-56
IF(STRESS(9)) V(9) = HOSTRS * SIN(PSIO)

DO 120 I = 1, 18
120 FM(I) = FMT(3)

K = 0
J = 0
DO 210 I = 2, 18
210 CONTINUE

IF(K.EQ.0) GO TO 180
WRITE(NOUT,9010) (T(J),J=5,8)
WRITE(NOUT,9013) (C(J),J=1,K)
RETURN

9000 FORMAT(IX,4A4/5X,'RADIAL',12X,'TANGENTIAL',12X,'VERTICAL')
9010 FORMAT(IX,9I4/5X,'RADIAL',12X,'TANGENTIAL',14X,'VERTICAL')
9013 FORMAT(IX,3(E12.4,1X))
SUBROUTINE JACOBI (H,U,ND,N,IVEC,W,IQ)

C-----------------------------------------------------------------------
C SUBROUTINE JACOBI TO COMPUTE EIGENVALUES AND EIGENVECTORS OF A
C SYMMETRIC MATRIX. H IS THE GIVEN MATRIX, THE DIAGONAL OF WHICH
C CONTAINS AFTER THE ITERATION THE EIGENVALUES OF H.

INTEGER FM(16), FMT(8)
LOGICAL EPS(6)

DIMENSION C(6), TKST(6,4)

COMMON/TAPE/NOUT

DATA TKST/ 'T0', 'TA', 'L', 'D I', 'S P', 'L A',
'4 CE', 'ME', 'IN',*/

DATA FMTFM(16)/
1*(6A4','.12X',',',E12'.3','(12A','4,48'.X',')'/

IF(L.NE.3) GO TO 10
FM(I)=FMT(6)
FM(2)=FMT(7)
FM(3)=FMT(8)
GO TO 20
FM(l)=FMT(l)
FM(2)=FMT(3)
FM(3)=FMT(3)
N=0
M2*K 2
DO 40 1=4^M,2
J=1/2-1
IF(.NOT.EPSCJ)) GO TO 30
FM(I)=FMT(4)
FM(I+1)=FMT(5)
C(N)=C(J)
GO TO 40
FM(I)=FMT(2)
FM(I+1)=FMT(3)
CONTINUE
IF(L.EQ.3) GO TO 60
IF(N.EQ.0) GO TO 50
WRITE(NOUT,FM) (TKST(I,3),I=1,6),(TKST(I,4),I=1,6)
RETURN
WRITE(NOUT,FM) (TKST(I,3),I=1,6),(TKST(I,4),I=1,6)
RETURN
END

SUBROUTINE JACOBI (H,U,ND,N,IVEC,W,IQ)
C U IS THE MATRIX, THE COLUMNS OF WHICH ARE THE EIGENVECTORS OF H.
IVEC=0 IF NO EIGENVECTORS ARE REQUIRED, IVEC=I IF THE EIGENVECTORS SHOULD BE CALCULATED.
The accuracy of the eigenvalues is about 1.OE-6, the accuracy of an eigenvector is about 1.OE-6/D, where D is the minimum distance of the corresponding eigenvalue from the other eigenvalues.
W and IQ are workspaces, which should be dimensioned in the calling program.

REAL H(ND,ND),U(ND,ND),W(ND)
INTEGER IQ(ND)
DOUBLE PRECISION TASI,CU,Z,Y,HTE,UTE
NMI1=N-I
IF(IVEC-1) 60,10,60
20 DO 40 J=IN-1,N
   U(I,J)=I.O
   GO TO 40
30 U(I,J)=0.0
40 CONTINUE
50 CONTINUE
60 DO 90 I=INMII
   W(I)=O.O
   IPLI=I+I
   DO 80 J=IPLI,N
      IPIV=IQ(I)
      IF(W(I)-ABS(H(I,J))) 70,70,80
      70 W(I)=ABS(H(I,J))
      IQ(I)=J
80 CONTINUE
90 CONTINUE
100 DO 120 I=N-1,1
   IF(I.EQ.1) GO TO 110
   IF(XMAX.GE.W(I)) GO TO 120
   XMAX=W(I)
   IPIV=I
110 XMIX=I
   IF(XMAX.GE.W(I)) GO TO 120
   XMAX=I
   JPIV=IQ(I)
120 CONTINUE
130 Z =H(IPIV,JPIV)-H(IPIV,JPIV)
   Y = 2.000*DBLE(H(IPIV,JPIV))
   TA = Y/(ABS(Z)+DSQRT(Z*Z+Y*Y))
   IF(Z.LT.0.000) TA=-TA
   CO = 1.000/DSQRT(1.000+TA*TA)

B-59
2596  SI =TA+CO 00035760
2597  HII=H(IPIV,IPIV) 00035770
2598  HJJ=H(JPIV,JPIV) 00035780
2599  HIJ=H(IPIV,JPIV) 00035790
2600  DO 140 K=1,N 00035800
2601  HTE=H(K,IPIV) 00035810
2602  H(K,IPIV)=DBLE(H(K,IPIV))*CO+DBLE(H(K,JPIV))*SI 00035820
2603  N(K,JPIV)=DBLE(H(K,JPIV))*CO-HTE*SI 00035830
2604  H(IPIVK)=H(KIPIV) 00035840
2605  H(JPIV,K)=H(K,JPIV) 00035850
2606  140 CONTINUE 00035860
2607  H(IPIV,JPIV)=O.O 00035870
2608  H(JPIV,IPIV)=O.O 00035880
2609  HH=H(IPIV,JPIV) 00035890
2610  IF(IVEC) 60,60,150 00035900
2611  IF(IVEC) 150 DO 160 K=I,N 00035910
2612  UTE=U(K,IPIV) 00035920
2613  U(K,IPIV)=DBLE(U(K,IPIV))*CO+DBLE(U(K,JPIV))*SI 00035930
2614  U(K,JPIV)=DBLE(U(K,JPIV))*CO-UTE*SI 00035940
2615  150 CONTINUE 00035950
2616  160 CONTINUE 00035960
2617  GO TO 60 00035970
2618  RETURN 00035980
2619  END 00035990
2620  SUBROUTINE ESORT (HU,ND,N,IVEC,N,IQ) 00036000
2621  C--------------------------------------------- 00036010
2622  C--------------------------------------------- 00036020
2623  C This routine sorts eigenvalues (and eigen 00036030
2624  C vectors) obtained from subroutine Jacobi. 00036040
2625  C H = original matrix(ND,ND). 00036050
2626  C U = eigenvector matrix(ND,ND). 00036060
2627  C ND = max. dimension of matrices. 00036070
2628  C N = actual dimension of matrices. 00036080
2629  C IVEC = 1 with eigenvectors. 00036090
2630  C = 0 no eigenvectors. 00036100
2631  C IQ = working space(ND). 00036110
2632  C--------------------------------------------- 00036120
2633  C--------------------------------------------- 00036130
2634  C--------------------------------------------- 00036140
2635  C--------------------------------------------- 00036150
2636  C--------------------------------------------- 00036160
2637  C--------------------------------------------- 00036170
2638  C--------------------------------------------- 00036180
2639  C--------------------------------------------- 00036190
2640  C--------------------------------------------- 00036200
2641  C--------------------------------------------- 00036210
2642  C--------------------------------------------- 00036220
2643  C--------------------------------------------- 00036230
2644  C--------------------------------------------- 00036240
2645  C--------------------------------------------- 00036250
2646  C--------------------------------------------- 00036260
2647  C--------------------------------------------- 00036270
2648  C--------------------------------------------- 00036280

B-60
W(I-1)+W(I) 00036290
W(I)=DUMMY 00036310
IQ(I-1)=IQ(I) 00036320
IQ(I)=DUMMY 00036330
J=I-1 00036340
IF (LOGIC) GO TO 30 00036350
IF (IVEC.EQ.0) GO TO 60 00036370
DO 40 I=1,N 00036380
U(J,K)=H(I,J) 00036410
50 H(I,I)=W(I) 00036450
RETURN 00036460
END 00036490
SUBROUTINE RNN(AA,BB,RN,ALOAD,ALIN,CAREA) 00036500
COMMON VSTR,STRLITER,STRL2 00036540
COMMON/RAOIAL/STSL,OSM,FS,SWL 00036550
WRITE(6,10) 00036560
10 FORMAT(//'PROGRAM USING STRAIN REPETITION NUMBER ............'//) 00036570
CALL FFRD(5,AA) 00036580
CALL FFRD(5,BB) 00036590
CALL FFRD(5,RN) 00036600
CALL FFRD(5,ALOAD) 00036610
CALL FFRD(5,ALIN) 00036620
CALL FFRD(5,DSM) 00036630
CALL FFRD(5,FS) 00036640
YY=ALOG10(RN) 00036650
Q=2*YY+BB 00036670
STRL=10.**Q 00036680
RETURN 00036690
END 00036700
SUBROUTINE RPAL(ALOAD,ALIN,CAREA) 00036710
COMMON/RAOIAL/STSL,DSM,FS,SWL 00036720
DATA A,B/0.58901,0.35486/ 00036730
CALL FFRD(5,DSM) 00036740
CALL FFRD(5,FS) 00036750
CALL FFRD(5,ALOAD) 00036760
CALL FFRD(5,ALIN) 00036770
RETURN 00036780
END 00036790
B-61
2702* CALL FFRD(5,CAREA,2)
2703* CALL FFRD(5,SWL,2)
2704* RN=20.*YRN
2705* RN=20.*YRN
2706* COV-RN/FAC 00036710
2707* RN=20.*YRN
2708* RN=20.*YRN
2709* RN=20.*YRN
2710* RN=20.*YRN
2711* RN=20.*YRN
2712* RN=20.*YRN
2713* RETURN
2714* END
2715* SUBROUTINE FLEXIES, EA ,ALOAD,ALIN,CAREA,XS,AS,BS,YRN,PRATIO
2716* C
2717* COMMON VSTRSTRL,ITER,STRL2
2718* COMMON /RADIAL/STSL,DSM,FS,SWL
2719* DATA AO/2.32E-03,-9.6347304E-05,2.9507649E-05,-4.2586473E-06,
2720* 13.0210971E-07,-1.1453280E-08,2.2311010E-10,-1.7523733E-12/
2721* DATA BO/1.54E-01,-1.7032892E-02,2.8018403E-03,-3.5283369E-04,
2722* 12.5877567E-05,-1.0485427E-06,2.1756275E-08,-1.7990976E-10/
2723* XS=ES/1000.
2724* AS=AO(1)+A012)*XS+AO( 3)*XS**2+AO( 5)*XS**3+AO( 7)*XS**4,
2725* BS=BO(1)+BO(2)*XS,BO(3)*XS**2,BO(4)*XS**3,BO(5)*XS**4+BO(6)
2726* BSNEGz-BS
2727* STRL=AS*YRN**BSNEG
2728* ACREPS=ALOG10(YRN*20./PRATIO)
2729* EAI=EA/14.22
2730* EALOG=ALOG10(EAI)
2731* STRL2=(ACREPS+2.665*EALOG+0.392)/5.
2732* STRL2=STRL2
2733* RETURN
2734* END
2735* SUBROUTINE POSTI(XTEMP,YTEMP,PRATIO)
2736* C
2737* REAL NU,ACCUR(3,LOAD,K5
2738* COMMDN/ASDT/LAYER.NLAYSM,R.Z,NU/]
2739* B-62

B-62
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B-63
2808* 2 FORMAT(80AI)
2809* NL=1
2810* 10 IF(NL.GE.80) NV=0
2811* IF(NL.GE.80) RETURN
2812* C
2813* C FIND FIRST NONE BLANK CHARACTER
2814* C
2815* DO 3 J=NL,80
2816* IF(ICRD(J).NE.IB) GO TO 5
2817* I=J
2818* 3 CONTINUE
2819* NL=I+1
2820* GO TO 10
2821* 5 NL=J
2822* IF(ICRD(NL).NE.IC) GO TO 4
2823* NV=0
2824* NL=NL+1
2825* RETURN
2826* 4 DD 6 J=NL,80
2827* IF(ICRD(J).EQ.IB) GO TO 7
2828* IF(ICRD(J).EQ.IC) GO TO 7
2829* 6 CONTINUE
2830* J=81
2831* 7 K=NL
2832* M=J-1
2833* ENCODE(40,2,IVAL(J)) (ICRD(I),I=M,K)
2834* NL=J=I
2835* L=J=K
2836* IF(L.LE.9) ENCODE(40,8,IFMT(I)) L
2837* IF(L.GE.10) ENCODE(40,8,IFMT(I)) L
2838* 8 FORMAT('(',I1,'I')
2839* 9 FORMAT('(',I1,'I')
2840* DECODE(IFMT,IVAL(1)) NV
2841* RETURN
2842* END
2843* SUBROUTINE FFRD(IFC,F,ID)
2844* COMMON/JRJ/ICRD(80),IVAL(80),NL
2845* DATA IB/1/I1/.IC/I1/.I
2846* IF(ID.NE.1) GO TO 10
2847* READ(IFC,2) (ICRD(I),I=1,80)
2848* 2 FORMAT(80AI)
2849* NL=1
2850* 10 IF(NL.GE.80) F=0.0
2851* IF(NL.GE.80) RETURN
2852* C
2853* C FIND FIRST NONE BLANK CHARACTER
2854* C
2855* DD 3 J=NL,80
2856* IF(ICRD(J).NE.IB) GO TO 5
2857* I=J
2858* 3 CONTINUE
2859* NL=I+1
2860* GO TO 10

B-64
2861*  5 NL=J
2862* IF (ICRD(NL).NE.IC) GO TO 4
2863* F=0.0
2864* NL=NL+1
2865* RETURN
2866* 4 DO 6 J=NL,BO
2867* IF (ICRD(J).EQ.IB) GO TO 7
2868* IF (ICRD(J).EQ.IC) GO TO 7
2869* 6 CONTINUE
2870 C J=J
2871 C 7 K=NL
2872 C M=J-I
2873 C ENCODE(40,2,IVAL(I)) (ICRD(I),I=K,M)
2874 C NL=J+I
2875 C L=M-K-1
2876 C IF (L.LE.9) ENCODE(40,8,IFMT(1)) L
2877 C IF (L.GE.10) ENCODE(40,9,IFMT(I)) L
2878 C 8 FORMAT('(F',II,'0)')
2879 C 9 FORMAT('(F',12,'0)')
2880 C DECODE(I,IFMT,IVAL(I)) F
2881 C RETURN
2882 C END
2883 BLOCK
2884 DATA 00037640
2885 C IN THE BLOCK DATA ARE STORED SUCCESSIVELY:
2886 C THE ABSCISSAE FOR THE LEGENDRE-GAUSS
2887 C QUADRATURE, STARTING IN A WITH THE 2-ND ORDER AND ENDING IN
2888 C ORDER AND ENDING IN N WITH THE 15-TH ORDER.
2889 C THE WEIGHTS FOR THE LEGENDRE-GAUSS
2890 C QUADRATURE, STARTING IN P WITH THE 2-ND ORDER AND ENDING IN
2891 C ORDER AND ENDING IN CC WITH THE 15-TH ORDER.
2892 C THE WEIGHTS FOR THE JACOBI-GAUSS QUADRATURE
2893 C OF THE 8-TH ORDER IN DD.
2894 C THE FIRST 149 ZEROS OF JO IN EE AND FF
2895 C THE FIRST 149 ZEROS OF J1 IN GG AND HH
2896 C REAL I,J,K,L,M,N
2897 DIMENSION A(2),B(3),C(4),D(5),E(6),F(7),G(8),H(9),I(10),J(11),K(12),L(13),M(14),N(15),O(16),P(17),Q(18),R(19),S(20),T(21),U(22),V(23),W(24),X(25),Y(26),Z(27)
2898 COMMON/GAUSS/AGAUSS(149,2),ZEROS(298)
2899 COMMON/GDATA/BZEROS(149,2),ZEROS(298)
2900 EQUIVALENCE (AGAUSS(1,2),A(1)),(AGAUSS(1,3),B(1)),(AGAUSS(1,4),C(1)),(AGAUSS(1,5),D(1)),(AGAUSS(1,6),E(1)),(AGAUSS(1,7),F(1)),(AGAUSS(1,8),G(1)),(AGAUSS(1,9),H(1)),(AGAUSS(1,10),I(1)),(AGAUSS(1,11),J(1)),(AGAUSS(1,12),K(1)),(AGAUSS(1,13),L(1)),(AGAUSS(1,14),M(1)),(AGAUSS(1,15),N(1)),(AGAUSS(1,16),O(1)),(AGAUSS(1,17),P(1)),(AGAUSS(1,18),Q(1))
2901 C REAL I,J,K,L,M,N
2902 DIMENSION A(2),B(3),C(4),D(5),E(6),F(7),G(8),H(9),I(10),J(11),K(12),L(13),M(14),N(15),O(16),P(17),Q(18),R(19),S(20),T(21),U(22),V(23),W(24),X(25),Y(26),Z(27)
2903 COMMON/GAUSS/AGAUSS(149,2),ZEROS(298)
2904 COMMON/GDATA/BZEROS(149,2),ZEROS(298)
2905 EQUIVALENCE (AGAUSS(1,2),A(1)),(AGAUSS(1,3),B(1)),(AGAUSS(1,4),C(1)),(AGAUSS(1,5),D(1)),(AGAUSS(1,6),E(1)),(AGAUSS(1,7),F(1)),(AGAUSS(1,8),G(1)),(AGAUSS(1,9),H(1)),(AGAUSS(1,10),I(1)),(AGAUSS(1,11),J(1)),(AGAUSS(1,12),K(1)),(AGAUSS(1,13),L(1)),(AGAUSS(1,14),M(1)),(AGAUSS(1,15),N(1)),(AGAUSS(1,16),O(1)),(AGAUSS(1,17),P(1)),(AGAUSS(1,18),Q(1))
2906 COMMON/GAUSS/AGAUSS(149,2),ZEROS(298)
2907 COMMON/GDATA/BZEROS(149,2),ZEROS(298)
2908 EQUIVALENCE (AGAUSS(1,2),A(1)),(AGAUSS(1,3),B(1)),(AGAUSS(1,4),C(1)),(AGAUSS(1,5),D(1)),(AGAUSS(1,6),E(1)),(AGAUSS(1,7),F(1)),(AGAUSS(1,8),G(1)),(AGAUSS(1,9),H(1)),(AGAUSS(1,10),I(1)),(AGAUSS(1,11),J(1)),(AGAUSS(1,12),K(1)),(AGAUSS(1,13),L(1)),(AGAUSS(1,14),M(1)),(AGAUSS(1,15),N(1)),(AGAUSS(1,16),O(1)),(AGAUSS(1,17),P(1)),(AGAUSS(1,18),Q(1))
### Table

<table>
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<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
<th>Column 7</th>
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<tr>
<td>6(HGAUSSI, 4), B1(1), (HGAUSSI, 5), S(1), (HGAUSSI, 6), T(1)</td>
<td>7(HGAUSSI, 7), V1(1), (HGAUSSI, 8), V1(1), (HGAUSSI, 9), W(1)</td>
<td>8(HGAUSSI, 10), X1(1), (HGAUSSI, 11), Z1(1)</td>
<td>9(HGAUSSI, 12), AA(1), (HGAUSSI, 13), BB(1), (HGAUSSI, 14), CC(1)</td>
<td>T(HGAUSSI, 15), DD(1), (BZERO(1, 1), EE(1), (BZERO(120, 1), FF(1))</td>
<td>11(BZERO(1), GG(1), (BZERO(120, 2), HH(1))</td>
<td>DATA A.B.C.D.E.F.G.H.I.J.K.L.M</td>
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</tbody>
</table>

### Data

```
0.2852315, 0.2852315, 0.7650553, -0.8302339, -0.4688488, 0.0000000, 0.0000000
```

### Additional Data

```
T(0.2920429, 0.2107044, 0.3464290, 0.5444444, 0.5444444, 0.3784749, 0.3784749)
```

---

### Notes

- **DATA** indicates the start of data in the table.

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### Source

- **DATA A.B.C.D.E.F.G.H.I.J.K.L.M**

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### Additional Observations

- The table contains numerical data with various sub-columns showing different sets of values.

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### Summary

- The page contains a dense table with various sets of data, formatted in a structured manner.

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### Additional Links

- The page contains a reference to specific data sets and values, indicating a structured approach to data presentation.

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### Conclusion

- The page provides a comprehensive view of data sets, likely intended for analysis or further computational purposes.