COMPUTER ANALYSIS OF STABILITY OF SLOPES

By

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TO THE SOUL OF MY FATHER
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SYNOPSIS

The main object of this thesis is to investigate the usefulness of the computer in solving problems involving the stability analysis of earth slopes.

The analysis is based on the assumption of a circular slip surface and three different versions of the 'method of slices' have been compared:

2. Bishop's Simplified Method.

To start with, the analysis by digital computer is considered where no man-machine interaction is involved.

Some special aspects are discussed in detail.

These are:

1. The Soil Frictional Force.
2. Forces on Sides of the Vertical Slices.
3. The Effect of Different Parameters on Safety Factor.

The computer method is further developed to allow for man-machine interaction in design by an interactive graphical display system. The two systems used in the analysis are:

2. Spindle System.

These are two software "packages" recently developed by the Computer-aided Design Project of Edinburgh University. The advantages of these systems in the design of earth slopes are investigated.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>(i)</td>
</tr>
<tr>
<td>Synopsis</td>
<td>(ii)</td>
</tr>
<tr>
<td>CONTENTS</td>
<td>(iii)</td>
</tr>
<tr>
<td>CHAPTER 1: INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER 2: STABILITY ANALYSIS</td>
<td>3</td>
</tr>
<tr>
<td>2.1: Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2.2: Basis of Stability Analysis Methods</td>
<td>4</td>
</tr>
<tr>
<td>2.2.1: Forces Causing Failure</td>
<td>4</td>
</tr>
<tr>
<td>2.2.2: Forces Resisting Failure</td>
<td>4</td>
</tr>
<tr>
<td>2.2.3: Factor of Safety</td>
<td>5</td>
</tr>
<tr>
<td>2.3: Derivation of Stability Equations</td>
<td>5</td>
</tr>
<tr>
<td>2.4: Determination of Safety Factor</td>
<td>9</td>
</tr>
<tr>
<td>2.4.1: Conventional Method</td>
<td>10</td>
</tr>
<tr>
<td>2.4.2: Bishop's Simplified Method</td>
<td>12</td>
</tr>
<tr>
<td>2.4.3: Bishop's Rigorous Method</td>
<td>14</td>
</tr>
<tr>
<td>CHAPTER 3: ANALYSIS BY COMPUTER</td>
<td>17</td>
</tr>
<tr>
<td>3.1: Computer Program</td>
<td>17</td>
</tr>
<tr>
<td>3.1.1: General</td>
<td>17</td>
</tr>
<tr>
<td>3.1.2: Flow Diagram</td>
<td>18</td>
</tr>
<tr>
<td>3.1.3: Conditions</td>
<td>20</td>
</tr>
<tr>
<td>3.1.4: Sign Convention</td>
<td>21</td>
</tr>
<tr>
<td>CHAPTER 4: APPLICATION TO SOME SPECIAL CASES</td>
<td>27</td>
</tr>
<tr>
<td>4.1: Soil Frictional Force</td>
<td>27</td>
</tr>
<tr>
<td>4.1.1: /</td>
<td></td>
</tr>
</tbody>
</table>
4.1.1: Fellenius Method 27
4.1.2: Bishop's Simplified Method 27
4.1.3: Conclusions 29
4.2: Determination of Side Forces 30
4.3: Parameters affecting Safety Factor 33
4.3.1: Conclusions 33
4.4: Application to Existing Slopes 35

CHAPTER 5: THE USE OF AN INTERACTIVE GRAPHICAL DISPLAY FOR DESIGN OF EARTH DAMS 36
5.1: General 36
5.2: Hardware Specifications 37
5.3: Solar System 37
5.3.1: Shift of Centre 38
5.3.2: Shift of Lowest Tangent 39
5.3.3: Alternative Design for the Slope 39
5.3.4: Advantages 40
5.4: Spindle System 41
5.4.1: Light Pen 41
5.4.2: Display of Safety Factor 42
5.4.3: Shift of Slip Circle 42
5.4.4: Shift of Lowest Tangent 43
5.4.5: Modification of Design 44
5.4.6: Advantages of Spindle System 45

CHAPTER 6: CONCLUSIONS 47
6.1: Factor of Safety 47
6.1.1: Comparison Between Current Methods of Stability Analysis 47
6.1.2:
6.1.2: Effective Normal Stress

6.2: Parameters Affecting Safety Factor

6.3: External Forces

6.4: Computer Graphical Method

6.4.1: Advantages

6.4.2: Future Developments

APPENDIX I

APPENDIX II

APPENDIX III

APPENDIX IV

APPENDIX V

APPENDIX VI

APPENDIX VII

APPENDIX VIII
CHAPTER 1

INTRODUCTION

For some time it has been possible to use a digital computer to perform the calculations necessary to determine the factor of safety of an embankment, such as an earth-dam or road embankment cross-section, using different methods of stability analysis. The application of the electronic computer has been urged by the need for a quicker and more efficient way of determining the safety factor of such slopes. The presentation of the program and the data to the computer is discussed in this thesis. In applying the computer to the problem of stability analysis of slopes, use is made of recently developed techniques involving direct communication between the designer and the computer so that the process of considering different possible designs is made more efficient.

If the computer is to be applied to the problem of stability analysis of slopes in a satisfactory way, two main aims have to be achieved:

1. Accuracy
2. Economy

The design of earth slopes involves a lot of repetitive calculation which leads inevitably to errors if the analysis is carried out by the laborious "hand" method. By using the electronic computer such errors can be avoided and a great deal of design time can be saved. In addition it becomes possible to/
possible to analyse a much large number of alternative designs. Consequently, the cost of the design is appreciably reduced.

The problem of earth-slope design requires a great deal of engineering judgment and alternative cross-sections have to be considered before the final design is chosen. This is ideally achieved if the engineer can interact with the computer during the analysis and introduce new modifications to the problem according to his judgment. The interactive graphical display system allows this interaction and facilitates better communication between the engineer and the computer by outputting the slope design in the form of a drawing displayed in front of the engineer who can study it and make the necessary changes accordingly.

In this thesis, the usefulness of the computer as an aid in analysis of stability of slopes in general and particularly in design of earth-dams is discussed in some detail. The advantages which can be gained by using an interactive graphical display are also investigated.
CHAPTER 2
STABILITY ANALYSIS

2.1 INTRODUCTION

In considering the computer analysis of stability of slopes, it is necessary to investigate the methods of numerical analysis currently in use and to suggest improvements to these where necessary.

In dealing with slope stability problems, some assumptions have to be made regarding the soil behaviour and the shape of the slip surface. In this thesis three main assumptions will be considered:

1. Failure takes place when the upper portion of the slope slides downward and outward upon the lower one along a fairly well defined slip surface. Both the lower and the upper portions are regarded as rigid in themselves (1, 2)*.

2. The slip takes place along a circular arc. This does not mean that it always occurs along a circular arc, but the assumption of a circular slip surface has been confirmed by many observations of slides which have taken place (3).

3. The factor of safety of the slope is assumed to be the same at all points of the failure surface.

To examine the stability of any slope, many possible slip

* Numerals in parentheses refer to corresponding items in references (Appendix I).
surfaces have to be analysed and the factor of safety for each surface calculated. The minimum such value is taken as the factor of safety of the slope, and the corresponding circle is known as the "Critical Circle".

2.2 BASIS OF STABILITY ANALYSIS METHODS

Methods dealing with stability analysis are based on three aspects:

1. Determination of forces causing failure of the slope.
2. Determination of forces resisting the failure.
3. Calculation of safety factor.

1.2.1 Forces Causing Failure

These are mainly the weight of the sliding portion, which depends upon the density of the soil, and the applied external forces if any.

1.2.2 Forces Resisting Failure

Failure of slopes is resisted by the shear strength of the soil along which failure is assumed to take place. Shear stress on soil is carried by soil particles while normal stress on any plane is the combination of:

a) The stress carried by the soil particles.

b) The pressure in the fluid in the void space.

Shear strength of the soil is a function of the cohesive and frictional forces of that soil. The frictional force depends on the normal stress carried by the soil particles rather than the total normal stress which includes the fluid pore pressure (4).

Thus the/
Thus the shear strength of the soil can be expressed as:

\[ T = c' + (\sigma' - u) \tan \phi' \]  

\[ \text{where:} \quad \begin{align*} 
    c' & \text{ denotes cohesion} \\
    \phi' & \text{ denotes angle of shearing resistance stress} \\
    \sigma' & \text{ denotes total normal stress} \\
    u & \text{ denotes pore pressure} 
\end{align*} \]

When applying equation (1.1) to stability analysis of slopes, the problem is considered as a two-dimensional problem (3). Kenney (5) stated that the error resulting from this assumption is always negligible when comparing the results of a 2-dimensional problem with those of a 3-dimensional one applied for the same slope.

**2.2.3 Factor of Safety**

In the analysis of stability of slopes, the limit design assumptions are usually considered. A state of limiting equilibrium is usually assumed along a trial slip surface. The factor of safety against failure is generally defined as the factor by which the shear strength of the soil is reduced to maintain limiting equilibrium. Thus the safety factor used in this thesis is given by:

\[ F = \frac{T}{S} \]

\[ \text{where:} \quad S = \text{mobilised shear stress, or shear stress required to maintain equilibrium.} \]

**2.3 DERIVATION OF STABILITY EQUATIONS**

Different methods/
Different methods are used in the stability analysis amongst which are:

1. $\phi$ -circle method.
2. Graphical Slices method.

In this thesis only the numerical slices method will be considered as this is the method which is suitable for use with a digital computer.

Consider the slope shown in fig. 1(a). Usually a thickness of one unit perpendicular to the cross-section of the slope is assumed in the analysis. A circular slip surface is then assumed and the portion of the slope above it is divided into vertical slices. Equilibrium conditions are to be applied for each individual slice and for the sliding mass as a whole to get the safety factor.

From equations (1.1) and (1.2):

$$s = \frac{1}{P} [c' + (\sigma_n - u) \tan \phi]$$

For each slice, total normal stress is given by:

$$\sigma_n = \frac{P}{l}$$

where: $P$ = Total normal force at the base of the slice
      $l$ = Length of the base of the slice.

Substituting for $\sigma_n$ in equation (1.3), we get:

$$s = \frac{1}{P} [c' + (\frac{P}{l} - u) \tan \phi]$$

Now, by considering the equilibrium of the slice shown in fig. 1(b)/
fig. 1(b) and equating the horizontal forces to zero, we get:

\[(E_1 - E_2) + P\sin \theta - sl\cos \theta = 0 \quad \ldots \ldots 1.5\]

Equating vertical forces to zero:

\[(X_1 - X_2) + w - P\cos \theta - sl\sin \theta = 0 \quad \ldots \ldots 1.6\]

where: \(E_1, E_2\) are the horizontal forces acting at the left and right sides respectively of the slice.

\(X_1, X_2\) are the vertical shear forces acting at the left and right sides respectively of the slice.

\(\theta\) is the angle made with the horizontal by the base of the slice.

\(w\) is the weight of the slice.

For the equilibrium of the whole mass above the slip surface, we have:

a) Horizontal forces:

\[\sum P\sin \theta - \sum sl\cos \theta = 0 \quad \ldots \ldots 1.7\]

b) Vertical forces:

\[\sum w - \sum P\cos \theta - \sum sl\sin \theta = 0 \quad \ldots \ldots 1.8\]

Equation (1.5) can be written as:

\[\sum (E_1 - E_2) + \sum P\sin \theta - \sum sl\cos \theta = 0 \quad \ldots \ldots 1.9\]

Comparing equations (1.7) and (1.9), the following equation can be obtained:

\[\sum (E_1 - E_2) = 0 \quad \ldots \ldots 1.10\]

Similarly equation (1.6) can be written as:

\[\sum (X_1 - X_2) + \sum w - \sum P\cos \theta - \sum sl\sin \theta = 0 \quad \ldots \ldots 1.11\]
and from (1.8) and (1.11), we get:

\[ \Sigma (x_1 - x_2) = 0 \] ............1.12

Kenney (5) when dealing with the side forces \( x \) and \( e \) showed that equations (1.10) and (1.12) are true only if there are no external forces applied on the face of the slope or if the external forces are in equilibrium. He also showed that when external forces, not in equilibrium, are involved in the problem fig. 1(d), equations (1.7) and (1.8) become:

\[ \Sigma P \sin \theta - \Sigma s1 \cos \theta - H = 0 \] ............1.7(a)

and:

\[ \Sigma w - \Sigma P \cos \theta - \Sigma s1 \sin \theta + V = 0 \] ............1.8(a)

where: \( H \) and \( V \) are the resultants of the horizontal and vertical external forces respectively.

By comparing equations (1.7a) and (1.9) he concluded that:

\[ \Sigma (E_1 - E_2) = -H \] ............1.10(a)

and from equations (1.8a) and (1.11):

\[ \Sigma (x_1 - x_2) = V \] ............1.12(a)

It is quite clear that the external forces \( V \) and \( H \) were not considered in the equilibrium of the individual slice (see equations (1.5) and (1.6)). This is acceptable for the case of the slices on which the external forces have no effect; but when considering the force equilibrium of slice "n" fig. 1(d), equations (1.5) and (1.6) become:

\[ (E_1 - E_2) + P \sin \theta - sl \cos \theta - h = 0 \] ............1.5(a)

and:

\[ (x_1 - x_2) + w - P \cos \theta - s1 \sin \theta + v = 0 \] ............1.6(a)
where: \( h \) and \( v \) are the horizontal and vertical external forces respectively acting on slice "n".

There is no apparent justification for the neglect of \( v \) and \( h \) in the force equilibrium of slice "n". It seems more logical if the comparison was made between equations (1.5a) and (1.7a) for the equilibrium in the horizontal direction, and equations (1.6a) and (1.8a) for equilibrium in the vertical direction. From this comparison, equations (1.10) and (1.12) can also be derived for the case when external forces are applied on the slope surface.

More evidence supporting this approach is given in Chapter 6.

2.4. DETERMINATION OF SAFETY FACTOR

Methods used for determination of safety factor differ mainly in three points:

1. The definition of factor of safety.
2. The assumed shape of the slip surface i.e. whether circular or non-circular.
3. The assumptions made about the side forces (\( x \) and \( z \) forces).

As mentioned before, the definition of safety factor given by equation (1.2) and the circular slip surface are the assumptions used in this thesis.

Regarding the side forces, three methods will be considered.
2.4.1 Conventional Method

This method is known as the "Ordinary Method" of slices or "Fellenius Method". It is also known as the "Conventional Method".

Considering fig. 1(a), and taking moments of forces acting on the whole mass above the slip surface about the centre of the slip circle, we get:

\[ \sum w x = \sum s l R \]  \hspace{1cm} .................................................. 1.13

where:
- \( w \) = weight of an individual slice.
- \( x \) = horizontal distance from centre line of slice to centre of circle.
- \( s \) = mobilised shear stress along the base of slice.
- \( l \) = length of base of slice.
- \( R \) = radius of slip circle.

It has been shown before that:

\[ s = \frac{1}{F} \left[ c' + \left( \sigma' - u \right) \tan \phi' \right] \]  \hspace{1cm} .................................................. 1.35

Hence equation (1.13) can be written as:

\[ \sum w x = \frac{R}{F} \sum \left[ c' l + (P - u l) \tan \phi' \right] \]

from which:

\[ F = \frac{R}{\sum w x} \sum \left[ c' l + (P - u l) \tan \phi' \right] \]  \hspace{1cm} .................................................. 1.14

By considering the equilibrium of one slice and resolving forces normal to the base of the slice, we get:

\[ P = (w + X_1 - X_2) \cos \theta - (E_1 - E_2) \sin \theta \]  \hspace{1cm} .................................................. 1.15

Substituting for \( P \) in equation (1.14):
\[ F = \frac{R}{\Sigma \text{wx}} \left[ c'1 + (w \cos \theta - ul) \tan \phi' \right] + \left[ (x_1 - x_2) \cos \theta - (E_1 - E_2) \sin \theta \right] \tan \phi' \]

Now, if the terms containing the side forces \( X \) and \( E \) are neglected, the expression for \( F \) becomes:

\[ F = \frac{R}{\Sigma \text{wx}} \left[ c'1 + (w \cos \theta - ul) \tan \phi' \right] \quad \ldots \ldots \quad 1.16 \]

By neglecting the \( X \) and \( E \) terms, the implied assumption used here is that the resultant of all forces on the sides of the slice acts parallel to the base of the slice. This method is used for many designs as it is quicker in application and does not involve many calculations. Generally, the factor of safety calculated by this method is smaller than that obtained for the same slope by the other two methods, and hence the design is usually on the safe side, but to some extent uneconomic.

When dealing with an earth slope with some external forces, eqtns. (1.13), (1.14), (1.15) and (1.16) become:

\[ \Sigma \text{wx} + \Sigma \text{vx} - \Sigma \text{hy}_h = \Sigma s1R \quad \ldots \ldots \quad 1.13(a) \]

\[ F = \frac{R}{\Sigma \text{wx} + \Sigma \text{vx} - \Sigma \text{hy}_h} \left[ c'1 + (P - ul) \tan \phi' \right] \quad \ldots \ldots \quad 1.14(a) \]

\[ P = (w + v + x_1 - x_2) \cos \theta - (E_1 - E_2 - h) \sin \theta \quad \ldots \ldots \quad 1.15(a) \]

\[ F = \frac{R}{\Sigma \text{wx} + \Sigma \text{vx} - \Sigma \text{hy}_h} \left[ c'1 + [(w + v) \cos \theta + h \sin \theta - ul] \right] \tan \phi' \quad \ldots \ldots \quad 1.16(a) \]

where: \( v \) and \( h \) are the vertical and horizontal forces respectively acting on the surface of an individual
of an individual slice (v and/or h might be equal to zero for some slices).

\( x_v \) and \( y_h \) are the distances from the lines of application of \( v \) and \( h \) respectively to the centre of the slip circle.

1.4.2 Bishop's Simplified Method

To determine the normal force \( P \) acting on the slice shown in fig. 1(b) all forces are resolved vertically:

\[
P \cos \theta + s_1 \sin \theta = w + x_1 - x_2
\]

or:

\[
P - u_1 = \frac{w + x_1 - x_2 - s_1 \sin \theta - u_1 \cos \theta}{\cos \theta}
\]

Substituting for \( s \) from equation (1.4) and rearranging the above equation:

\[
(P - u_1) \cos \theta = w + (x_1 - x_2) - u_1 \cos \theta - \frac{c'_1 \sin \theta}{F}
\]

or:

\[
P - u_1 = \frac{w + (x_1 - x_2) - u_1 \cos \theta - \frac{c'_1 \sin \theta}{F}}{\cos \theta + \frac{\tan \phi' \sin \theta}{F}}
\]

Substituting in equation (1.14) we get:

\[
F = \frac{R}{\sum_{wx}} \left[ c'1 + \left\{ \frac{w + (x_1 - x_2) - u_1 \cos \theta - \frac{c'_1 \sin \theta}{F}}{\cos \theta + \frac{\tan \phi' \sin \theta}{F}} \right\} \tan \phi' \right]
\]

or:

\[
F = \frac{R}{\sum_{wx}} \left[ c'b + \left\{ \frac{w + (x_1 - x_2) - ub}{\cos \theta + \frac{\tan \phi' \sin \theta}{F}} \right\} \tan \phi' \right]
\]

where: \( b = \) width of the slice (measured horizontally)

The pore pressure/
The pore pressure can also be expressed in terms of the pore pressure ratio \( r_u \) given by:

\[
\frac{u}{w} = \frac{ub}{u}
\]

Now, if the soil properties: cohesion \( c' \), angle of friction \( \phi' \), weight per unit volume \( w \), and pore pressure \( u \) (or pore pressure ratio \( r_u \)) are known, then for a certain assumed slip circle of radius \( R \), the only remaining unknowns are side forces \( X_1 \) and \( X_2 \) and the factor of safety \( F \).

If the effect of \( X \)-forces on the calculation is neglected, or in other words the term \( (X_1 - X_2) \) is put equal to zero for each slice, then equation (1.18) can be solved for \( F \). By neglecting the effect of the vertical shear forces, the implied assumption used here is that the side forces act horizontally.

Now, equation (1.18) can be solved for \( F \) by taking the following steps (simple iteration):

1. An initial value for \( F \) is assumed, which is, for convenience, taken as the factor of safety calculated by the first method for the same slip surface.
2. This assumed \( F \) is substituted in the right hand side of equation (1.18) (with \( (X_1 - X_2) = 0 \)) and \( F \) on the left hand side of the equation is obtained.
3. The new value of \( F \) is then substituted in the right hand side of the equation to calculate another value for \( F \) on the left hand side of the equation.

Step (3) is to be repeated until the obtained value for \( F \) is approximately the same as the last value substituted in the right hand/
the right hand side of the equation. Convergence is usually obtained after three or four iterations if the initial assumed value for \( F \) is reasonable. Alternatively, by means of a slight modification of steps 2 and 3, the Newton-Raphson iteration method (6) can be used.

Bishop's simplified method is lengthy and needs a great degree of accuracy, but with the aid of the computer many assumed slip surfaces can be considered with great accuracy and in a very short time.

Here again the introduction of external forces gives equations (1.17) and (1.18) the following forms:

\[
P - u\ell = w + v + (X_1 - X_2) - u\ell \cos \theta - \frac{c'\ell \sin \theta}{\cos \theta + \tan \phi' \sin \theta} \frac{F}{F}
\]

\[
F = \frac{R}{w + v + (X_1 - X_2) - u\ell \tan \phi' + \tan \phi' \sin \theta} \frac{1.17(a)}{1.18(a)}
\]

2.4.3 Bishop's Rigorous Method

This is a more rigorous method in which the effect of the side forces is fully considered when using equation (1.18).

Consider the force equilibrium of the slice shown in fig. 1 (b) by resolving forces in a direction tangential to the slip surface:

\[
(E_1 - E_2) \cos \theta = s\ell - (w + X_1 - X_2) \sin \theta
\]

\[
\ldots \ldots \ldots 1.19
\]
By substituting for \( s \) from equation (1.4) and rearranging the above equation, we get:

\[
(E_1 - E_2) = \frac{1}{F} \{ c' l + (P - ul)\tan \phi \} \sec \theta - (w + X_1 - X_2) \tan \theta
\]

Now applying this equation for all slices within the slip surface:

\[
\sum (E_1 - E_2) = \sum \left[ \frac{\sec \theta}{F} \{ c' l + (P - ul)\tan \phi \} - (w + X_1 - X_2) \tan \theta \right]
\]

Comparing equations (1.14) and (1.18), the above equation can be written as:

\[
\sum (E_1 - E_2) = \sum \left[ \frac{\sec \theta \{ c' l + (w + X_1 - X_2) \tan \phi \}}{\cos \theta + \tan \frac{\phi'}{\sin \theta}} \right] \\
- (w + X_1 - X_2) \tan \theta \]..........1.20

It has been shown before that:

\[
\sum (E_1 - E_2) = 0 \]..........1.10

and:

\[
\sum (X_1 - X_2) = 0 \]..........1.12

To satisfy equation (1.10), the right hand side of equation (1.20) should be equated to zero. This can be achieved by choosing suitable values for \( X_1 \) and \( X_2 \) to fit in equation (1.20). These can be found by applying the iteration method to this equation for the determination of the \( x \)-force distribution, assuming the latter to increase linearly from zero to a peak value at the mid-ordinate of the sliding mass and then to decrease linearly to zero again. This triangular distribution is chosen as it has approximately a similar shape to the one obtained by Bishop (5). The steps followed in this case are as follows:
1. A reasonable $X$-force distribution is assumed and the values of $X_1$ and $X_2$ for each slice are found and substituted in equation (1.20). As mentioned by Bishop (7) the variations in the value of $F$ corresponding to the different possible $X$-distributions are small.

2. The value of $F$ found by equation (1.18) is then substituted in the right hand side of equation (1.20).

3. The $X$-distribution is readjusted until finally the right hand side of equation (1.20) has a value very close to zero.

4. Knowing the new $X$-distribution, $X_1$ and $X_2$ for each slice are recalculated and substituted in equation (1.18) together with the value of $F$ used in step 2. In this way a new value of $F$ is determined.

If the value of $F$ obtained in step 4 is not equal to that used in step 2, the process is repeated by going back to step 2, 3 and 4 until it converges. In most cases four or five iterations will be enough to get the final answer.

Now, if there are some external forces $V$ and $H$ acting on the face of the slope, equations (1.19) and (1.20) become:

\[
(E_1 - E_2) \cos \Theta = s - (w + v + X_1 - X_2) \sin \Theta + h \cos \Theta
\]

and:

\[
\sum (E_1 - E_2) = \sum [\frac{\sec \Theta \cdot b + (w + v + X_1 - X_2 - ub) \tan \phi'}{\cos \Theta + \frac{\tan \phi'}{\sin \Theta}}]

- (w + v + X_1 - X_2) \tan \Theta - h \cos \Theta]
\]
FIG. 1: FORCES IN THE SLICES METHOD
CHAPTER 3
ANALYSIS BY COMPUTER

3.1 COMPUTER PROGRAMS

3.1.1 General

In this chapter the procedure followed to prepare the computer program is discussed in some detail. Although Fortran is the language used in this analysis, yet the program may be adapted, with some changes, to other computer languages. The computer used to perform the calculations and analysis is the 4130 Elliott computer.

To simplify the problem and to present it to the computer in a clear form, the following procedure is followed when preparing the computer program:

1. Each line (or 'contour') defining the boundary of a soil within the earth slope is given a number, top contour being number 1. Similarly, the topmost soil is referred to as soil number 1 and the one below it as soil number 2 and so on for the other layers of soils.

2. The four properties of each soil are numbered in the following order:
   
   Property Number 1: soil density $\gamma$
   Property Number 2: cohesion $c'$
   Property Number 3: $\tan \phi'$
   Property Number 4: pore pressure ratio $\gamma_u$
3. All points on any contour are also given numbers starting from 1 in ascending order going from left to right of the figure, e.g. in fig. 2(a).

For contour 1, points A, B, C, D are referred to as points numbers 1, 2, 3, 4 respectively.

4. Finally to distinguish between the X-co-ordinate and the Y-co-ordinate of each point on the cross-section, every point will be defined in the computer program as follows:

A (I, J, K)

I : defines the number of the contour on which the point lies.

J : specifies whether it is the X-co-ordinate or Y-co-ordinate of the point; J = 1 for the X-co-ordinate, J = 2 for the Y-co-ordinate.

K : defines the number of the point.

In some cases the pore pressure ratio might not be presented to the computer with the other soil properties. Instead, the piezometric level is defined in the data and accordingly the computer will calculate the pore pressure at any point within that particular soil from the corresponding piezometric level.

3.1.2 Flow Diagram

Consider the simple slope shown in fig 2(a) which consists of two soil layers on a solid foundation. The X and Y axes are chosen with origin usually at the bottom left hand corner of the figure. The flow diagram, fig. 3, shows the following major steps followed by the computer in this analysis:
1. The co-ordinates of all points defining the geometry of the cross-section are read from the data tape.

2. The soil properties and pore pressure distribution are also read from the data tape.

3. The cross-section is divided into vertical slices, the width of each slice being limited by a maximum value given in the data tape. Moreover, each point of intersection of straight lines defining the boundaries of the soil layers must lie on one of the vertical lines separating the slices - see fig. 2(a).

4. Determination of the X-co-ordinate of centre line of each slice.

5. Determination of the Y-co-ordinate of the points of intersection of contours and centre lines of slices, i.e. points A, B and C in fig. 2(b).

6. From the given soil density and the external applied forces on the slope, if any, the weight of each zone within the slice is calculated i.e. weights of zones FGHI and IHJK.

7. For a particular assumed slip circle whose lowest tangent and co-ordinates of centre are given, the Y-co-ordinate of point P - fig. 2(b) - is determined for each slice cut by this circle and the number of slices within this circle is obtained. The weight of each slice above the slip surface is also calculated and stored.
FIG. 2: AN EARTH DAM EXAMPLE AND A TYPICAL SLICE
Read Max. Width Of Slice, And Number Of Contours

Read Slope Data

Divide Slope Cross-section Into Vertical Slices

Read Soil Data

Calculate The Weight Of Each Slice

Read Circle Data

Does This Circle Satisfy All Conditions?

YES

Calculate Factor Of Safety F

NO

FIG. 3: FLOW DIAGRAM
8. The factor of safety is calculated for this assumed slip surface and the same procedure is repeated for other specified slip circles.

2.1.3 Conditions

At a certain stage of the analysis it might be necessary to stop the calculation for a particular assumed slip surface. This could be the case when the surface considered is obviously not the critical one. To save the designer's and computer's time, further calculations for such cases can be terminated by including the following conditions in the computer program:

1. A limit for the minimum number of slices which should be included in the slip surface is stated in the program. If the actual number of slices within the considered slip surface is less than that limit, no further calculations are to be carried by the computer for that particular slip surface - fig. 4(a).

2. If the circle considered does not cut the slope - fig. 4(b), cuts bottom contour which defines the boundary of the solid foundation - fig. 4(c), cuts the slope at two different points A and B - fig. 4(d), or cuts either or both of the two edges of the slope - fig. 4(e), calculations are stopped and the next slip surface is considered.

3. If the top contour which defines the surface of the slope cuts the upper semi-circle, no further calculations are carried out for that particular circle - fig. 4(f).

The results/
FIG. 4: SLIP CIRCLES NOT SATISFYING CONDITIONS
The results of the analysis are printed by the Line Printer fig. 5 giving the number of the circle, the X and Y-co-ordinates of its centre, the ordinate of its lowest tangent and the values for F calculated according to the three methods discussed in chapter 1. If the circle considered does not satisfy any of the above conditions, the reason will be stated in the output.

3.1.4 _Sign Convention_

For each slice within the slip surface, the following equations have been used - see fig. 6(a):

Moment of weight of slice above slip surface about the centre of the slip circle is given by:

\[ M = wx \]

or: \[ M = wR \sin \theta \] ..........2.1

Resolving forces vertically:

\[ F \cos \theta + s_1 \sin \theta - (w + X_1 - X_2) = 0 \] ..........2.2

Resolving forces parallel to the slip surface:

\[ (E_1 - E_2) \cos \theta + (w + X_1 - X_2) \sin \theta - s_1 = 0 \] ..........2.3

From equation (2.2), equation (1.20) is derived:

\[ \sum (E_1 - E_2) = \sum \left[ \frac{\sec \theta}{F} \left\{ \frac{c'b + (w + X_1 - X_2 \tan \phi')}{\cos \theta + \frac{\tan \phi' \sin \theta}{F}} \right\} - (w + X_1 - X_2) \tan \theta \right] \] ..........1.20

The expressions used in the computer program for \( \sin \) and \( \cos \) are as follows:

\[ \sin \theta = \frac{(X_C - X_2)}{R} \] ..........2.4
\[
\cos \theta = \frac{(Y_C - O)}{R}
\]

where \(XC, YC\) are the \(X\) and \(Y\)-co-ordinates of slip circle centre.
\(R\) is its radius.
\(X2\) is the \(X\)-co-ordinate of the centre line of the slice.
\(C\) is the \(Y\)-co-ordinate of the point of intersection of the circle and the centre line of the slice.

To explain the sign convention used in this analysis, two types of slip are to be considered:

1. **Slip to the Right (fig. 6(b)):**

   In this case the centroid of the sliding mass is to the left of the centre 0 of the slip circle considered. It follows that for the greater portion ABCDEA of the sliding mass, \(X2\) will be less than \(XC\), and therefore \(\sin \theta\) will be positive resulting in a positive value for \(M\) given by equation (2.1) in an anti-clockwise direction for all the slices to the left of 0. On the other hand, \(X2\) for the smaller portion CDFC is greater than \(XC\), and hence \(M\) will be negative in a clockwise direction.

   In a homogeneous slope this latter clockwise moment will be balanced by the anti-clockwise moment of the portion CDEC, and so finally we remain with the anti-clockwise moment of the portion ABCEA which is positive.

   To explain the sign convention with regard to forces, two slices A and B - fig. 6(b) - to the left and right of 0 are considered:
Slice A

By considering the force equilibrium and resolving parallel to the slip surface, we get:

\[(E_1 - E_2) \cos \theta + (w + X_1 - X_2) \sin \theta - sl = 0\]

As \(\sin \theta\) is positive in this case, the above equation is the same as equation (2.3) for the general case. It also follows from this equation and equation (1.20) that for each slice:

\begin{align*}
(E_1 - E_2) &= \frac{\sec \theta}{F} \left[ \frac{c'b + (w + X_1 - X_2) \tan \phi}{\cos \theta + \frac{\tan \phi \sin \theta}{F}} \right] \\
&\quad - (w + X_1 - X_2) \tan \theta \\
&= \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldOTS
2. **Slip to the Left (fig. 7):**

The centroid of the sliding mass is to the right of centre O, and so for the greater portion ABCDEA, \(x_2\) is greater than \(x_C\) which means negative value for \(\sin \theta\) and consequently negative value for \(M\). For the smaller portion CDFC, \(x_2\) is less than \(x_C\) and, therefore, \(M\) will be positive. The net moment for a homogeneous slope is that of the portion ABCDEA with a negative value. The absolute value of this moment is the one substituted for \(\xi \omega x\) in the equation for \(F\).

**Slice A**

Resolving forces parallel to the slip surface:

\[
(E_2 - E_1) \cos \theta - (w + X_1 - X_2) \sin \theta - sl = 0
\]

If the general equation (2.3) is to be applied to slice A, \(\sin \theta\), which is originally positive in this case, should be taken as negative, and term \((E_1 - E_2)\) of equation (2.3) should be replaced by \((E_2 - E_1)\). With \(\sin \theta\) taken as negative, equation (2.2) can be applied to this slice and to slices to the left of O.

**Slice B**

In a similar way:

\[
(E_2 - E_1) \cos \theta + (w + X_1 - X_2) \sin \theta - sl = 0
\]

\(\sin \theta\) is originally negative, so for equation (2.3) to be used in this case, \(\sin \theta\) is given a positive value and term \((E_1 - E_2)\) of equation (2.3) is replaced by \((E_2 - E_1)\).

Also for this slice:

\[
P \cos \theta + sl \sin \theta - (w + X_1 - X_2) = 0
\]
With sin $\theta$ taken as positive, this expression is the same as that of the general case given by equation (2.2).

**Summary of Sign Convention**

1. **Slip to the Right (fig. 6(b))**:
   a) Angle $\theta$ made by the slip surface with the horizontal is positive for the part of the sliding mass to the left of the centre of the slip circle. $\theta$ is taken as negative for the part to the right of the centre. Thus sin $\theta$ as given by the equation (2.4) is substituted in the general equations for all slices within the slip surface.
   b) The right hand side of the general equation (1.20) is to be equated to $\Sigma(E_1 - E_2)$ for all slices.

2. **Slip to the Left (fig. 7)**:
   a) Angle $\theta$ is taken as positive for the part to the right of the centre 0 and negative for the part to the left of 0; i.e. equation (2.4) is given the form:
   $$\sin \theta = -\frac{(X_1 - X_2)}{R} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.4(a)$$
   and accordingly sin $\theta$ is determined for all slices above the slip surface.
   b) The right hand side of equation (1.20) is equated to $\Sigma(E_2 - E_1)$ for all slices.

3. **X-Forces**

In all cases considered, the $X_1$ and $X_2$ vertical shear forces are initially assumed to act downward and upward respectively;
respectively; $X_1$ being to the left and $X_2$ to the right of the slice.

All the necessary sign adjustments explained in the previous part of this chapter are dealt with by the computer according to special instructions included in the program.
FIG. 6: SIGN CONVENTION – SLIP TO THE RIGHT
FIG. 7: SIGN CONVENTION—SLIP TO THE LEFT
CHAPTER 4
APPLICATION TO SOME SPECIAL CASES

4.1 SOIL: FRICTIONAL FORCE

4.1.1 Fellenius Method (fig. 8)

The definition of the factor of safety is given by:

\[ F = \frac{\text{Moment of Forces Resisting Failure}}{\text{Moment of Forces Causing Failure}} + N' \tan \phi \]

or:

\[ F = \frac{\sum (c' l + N' \tan \phi)}{\sum w \sin \theta} \]

where \( N' \) = Effective normal force at base of slice

To determine \( N' \), forces are resolved normal to the slip surface:

\[ P = w \cos \theta \]

where \( P = N' + u \)

\( u \) being the pore pressure

\[ . \hspace{1cm} N' = w \cos \theta - u \]

As the forces acting on the vertical sides of the slices do not appear in the expression for \( P \), the implied assumption used here is that the resultant of the side forces acts parallel to the slip surface. It has been mentioned by Whitman and Bailey (8) that this condition is not met with for all slices, and so it follows that the calculated factor of safety is approximate.

4.1.2 Bishop's Simplified Method (fig. 8)

In this method, a different approach is followed to determine \( N' \) by resolving forces vertically:

\[ P \cos \theta = w - s \sin \theta \]

and the expression for \( N' \) is given by:
As equation (4.3) does not include the side forces, the assumption implied here is that the resultant of side forces acts horizontally. Although this does not hold true for all slices in every case considered, yet the safety factor calculated by this method is very close to that obtained when using the more accurate method (8).

The frictional force which is a component of the resisting force at the base of the slice is given by:

\[ \text{Frictional Force} = N' \tan \phi \]

It can be seen from equation (4.3) that \( N' \) can have a negative value or zero for some slices. This is considered to be the difficulty with Bishop's Method (8). It is also clear that the same may be said about Fellenius Method when examining equation (4.2) which may give a negative or zero value for \( N' \).

As a result of \( N' \) being negative for some slices, the frictional component of the resisting force will have a negative value for those particular slices. Logically negative friction, i.e. having the same direction as that of forces causing the failure, cannot exist, and therefore some precautions should be considered when using Bishop's Method in the stability analysis of slopes. It is therefore necessary to check whether, for any slice, \( N \) has a negative, zero, or positive value:

**Case 1:** With \( N' \) negative:

The value of \( N' \) is put equal to zero so that the frictional force in this case would be equal to zero.
\[ s_l = \frac{1}{F}(c_l + N' \tan \phi') \]

- **S** = Mobilised Shear Strength At The Base Of The Slice
- **P** = Total Normal Force At The Slice Base
- **N** = Effective Normal Force At Slice Base
- **W** = Weight Of The Slice
- **F** = Factor Of Safety

**FIG. 8: FELLENIUS AND BISHOP'S SIMPLIFIED METHODS**
Case 2: With N' zero:
The same value for N' is used giving zero frictional force.

Case 3: With N' positive:
This is the most common case with frictional force having a positive value.

The computer method has been used to solve some earth slope problems Figs. 9 and 10 in which the above checks have been applied. The results are compared with those obtained for the same slopes (with N' negative for some slices) in table 1.

4.1.3 Conclusions

1. The combination of high pore pressure and safety factor less than unity results in a negative value for the soil frictional force at the slices where angle $\theta$ is large.

2. In some cases, slices, which have positive values for N' when using equation (1.18) with $(x_1 - x_2) = 0$ for every slice, might have negative values for N' given by equation (1.17) when the side forces X and E are included in the analysis. This is found to be the case, when, in addition to the combination of high pore pressure, large $\theta$ and small F, $(x_1 - x_2)$ has a negative value.

3. As frictional force always acts in the direction opposite to that of the forces causing failure, N' should always be assumed to be positive or zero.

4. The adjustment of the frictional force to zero when it has a/
(a) EXAMPLE 1: WITH VARIABLE $r_u$

- $c' = 90 \text{ lb/ft}^2$
- $\phi' = 30^\circ$
- $Y = 125 \text{ lb/ft}^3$

(b) EXAMPLE 2: WITH VARIABLE ANGLE OF SLOPE

- $c' = 80 \text{ lb/ft}^2$
- $\phi' = 40^\circ$
- $Y = 120 \text{ lb/ft}^3$
- $r_u = 0$

FIG. 9: SIMPLE EARTH SLOPE EXAMPLES
(a) **EXAMPLE 3**: WITH VARIABLE $\phi'$

- $c' = 350 \text{ lb/ft}^2$
- $\gamma = 145 \text{ lb/ft}^3$
- $r_u = 0.5$

(b) **EXAMPLE 4**: WITH VARIABLE $c'$

- $\phi' = 30^\circ$
- $\gamma = 125 \text{ lb/ft}^3$
- $r_u = 0.45$

(c) **EXAMPLE 5**: WITH VARIABLE NUMBER OF SLICES

- $c' = 85 \text{ lb/ft}^2$
- $\phi' = 30^\circ$
- $\gamma = 150 \text{ lb/ft}^3$
- $r_u = 0.45$

**FIG. 10**: SIMPLE EARTH SLOPE EXAMPLES
<table>
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<th>Factor of Safety F</th>
<th>Bishop's Simplified Method</th>
<th>Bishop's Rigorous Method</th>
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**TABLE 1: COMPARISON BETWEEN FACTORS OF SAFETY CALCULATED WHEN:**

1. SOIL FRICTIONAL FORCE MAY BE NEGATIVE ON SOME SLICES
2. SOIL FRICTIONAL FORCE IS ALWAYS TAKEN AS POSITIVE OR ZERO

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**TABLE 1:** COMPARISON BETWEEN FACTORS OF SAFETY CALCULATED WHEN:

1. SOIL FRICTIONAL FORCE MAY BE NEGATIVE ON SOME SLICES
2. SOIL FRICTIONAL FORCE IS ALWAYS TAKEN AS POSITIVE OR ZERO

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<td>1.594</td>
<td>35</td>
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</tbody>
</table>
has a negative value leads in many cases to a different critical circle when using the conventional method. With the other two methods, however, the position of the critical circle is generally the same before and after the adjustment.

5. The number of slices with negative frictional force is found to decrease as the number of iterations for F increases when using Bishop's simplified method.

4.2 DETERMINATION OF SIDE FORCES

Most of the methods used in the stability analysis of slopes differ in the assumptions made when dealing with the side forces and their line of application, known as line of Thrust. A well known approach to this problem assumes the location of the line of thrust to be known, usually at the lower third of the sliding mass and accordingly the magnitudes of these forces are determined (5).

In this thesis the procedure discussed in chapter 2 is followed by assuming an initial triangular distribution of X-forces, see fig. 11, and iterating to obtain a distribution of this type which satisfies equations (1.10) and (1.20). From the determined X-force distribution the vertical shear forces along the sides of each slice can be obtained. The next step is to substitute these vertical shear forces ($X_1$ and $X_2$) in equation (1.20) to find $(E_1 - E_2)$ for each slice.

To determine the E-force distribution along the sliding mass/
mass and the position of line of thrust, the moment equilibrium of each slice is considered.

Fig. 12 (b) shows slice 1 of the sliding mass shown in fig. 12(a). According to the initial assumption made about the X and E force distributions, both X₁ and E₁ for slice 1 are equal to zero. Hence E₂ has the value obtained from equation (1.20) for (E₂ - E₁). By taking moments of all the forces acting on slice 1 about K, we get:

\[
\alpha_2 = \frac{-bX_2}{2E_2}
\]

For slice 2 fig. 12(c), E₁ has the same magnitude as that of E₂ of slice 1, and, moreover, they act at the same point on the vertical line separating the two slices. The vertical distance between point K of slice 1 and point G of slice 2 can be determined from their corresponding y-co-ordinates calculated and stored already by the computer. Hence the distance \( \alpha_1 \) shown in slice 2 can easily be determined.

The moment equilibrium of forces acting on slice 2 about G is given by the expression:

\[
\frac{b}{2} (X_1 + X_2) + E_2 \alpha_2 - E_1 \alpha_1 = 0
\]

Knowing the magnitude and point of application of E₁, the magnitude of E₂ can be determined from the value of (E₂ - E₁) obtained from equation (1.20). Substituting this value of E₂ in the above expression, this distance \( \alpha_2 \) will be given by:

\[
\alpha_2 = \frac{2E_1 \alpha_1 - b(X_1 + X_2)}{2E_2}
\]

In this way/
In this way the position of the line of thrust can be determined for all slices within the slip surface.

Two checks are applied to the results obtained by this method (5):

1. The determined vertical shear force $X_m$ should not exceed the potential shear strength of the soil along the vertical plane which is given by:

$$S_v = \frac{\sigma' h + (\frac{E_1 + E_2}{2} - uh) \tan \phi}{F}$$

where $h =$ height of the slice.

The vertical shear force is given by:

$$X = \frac{X_1 + X_2}{2}$$

2. The shapes of the determined $X$ and $F$ distributions should be similar to those found by Bishop when investigating the stress distribution within an elastic embankment (5).

From the results obtained for the examples considered the following conclusions are reached:

(i) The position of the Line of Thrust is found in most cases to be very close to the lower third of the sliding mass. In some few cases it is found to lie above the lower third and within the lower half of the sliding mass - see figs. 13-15.

(ii) For almost all the cases considered the potential shear strength along vertical planes is not exceeded.
exceeded by the vertical shear force - see Tables 2-5.

(iii) The shapes of the X and E distributions agree approximately with those found by the stress analysis of an elastic embankment - see figs. 12-15.

4.3 PARAMETERS AFFECTING SAFETY FACTOR

The main variables upon which the factor of safety depends are:

1. The geometry of the cross-section of the slope.
2. The pore pressure \( u \).
3. The angle of shearing resistance \( \phi \).
4. The soil cohesion \( c' \).
5. The soil density \( \gamma \).

To see the effect of each of these factors on the safety factor, the computer method is applied to some examples and the results are given in tables 6-10. Also the relationship between some of these variables and the safety factor are shown in figs. 16-20.

On the other hand, the effect of the number of slices considered within the assumed slip circle on the factor of safety is shown in table 10.

4.3.1 Conclusions

From these results the following conclusions are reached:

1. For a given cross-section and specified shear strength parameters/
FIG. 11: DETERMINATION OF SIDE FORCES
FIG. 2: DETERMINATION OF LINE OF THRUST

(a) Slice 1

(b) Slice 1

(c) Slice 2

FIG. 12: DETERMINATION OF LINE OF THRUST
FIG. 13: EXAMPLE 2—LINE OF THRUST AND SIDE FORCES DISTRIBUTIONS
\[ \gamma = 145 \text{ lb/ft}^3 \]
\[ C' = 350 \text{ lb/ft}^2 \]
\[ \phi' = 37.5^\circ \]
\[ T_u = 0.4 \]

FIG. 14: DAER DAM—LINE OF THRUST AND SIDE FORCES DISTRIBUTIONS
FIG. 15: FOLKESTONE WARREN 1940 LANDSLIP—LINE OF THRUST AND SIDE FORCES DISTRIBUTIONS

CHALK:
\[ \gamma = 130 \text{ lb/ft}^2 \]
\[ c' = 0 \]
\[ \phi' = 20^\circ \]

CLAY:
\[ \gamma = 130 \text{ lb/ft}^2 \]
\[ c' = 0 \]
\[ \phi' = 18^\circ \]

(PORE PRESSURE \( u \) CALCULATED FROM PIEZ. LEVEL)
<table>
<thead>
<tr>
<th>Pore Pressure Ratio $r_u$</th>
<th>Factor of Safety $F$</th>
<th>Slice No.</th>
<th>Potential Shear Strength Along Vertical Plane $S_v$</th>
<th>Vertical Shear Force $X_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c'h + \frac{E_1 + E_2}{2} - uh \tan \phi$</td>
<td>$\frac{X_1 + X_2}{2}$</td>
</tr>
<tr>
<td></td>
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**TABLE 2: EXAMPLE 1 - COMPARISON BETWEEN POTENTIAL SHEAR STRENGTH AND VERTICAL SHEAR FORCE ALONG VERTICAL PLANES.**
<table>
<thead>
<tr>
<th>Angle of Slope $\beta$</th>
<th>Factor of Safety $F$</th>
<th>Slice no.</th>
<th>Potential Shear Strength Along Vertical Plane $S_v = \left[ \frac{c'h + \left( \frac{1 + E}{2} - uh \right) \tan \phi'}{F} \right]$ (lbs)</th>
<th>Vertical Shear Force $X_m = \frac{X_1 + X_2}{2}$ (lbs)</th>
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**TABLE 3:** EXAMPLE 2 - COMPARISON BETWEEN POTENTIAL SHEAR STRENGTH AND VERTICAL SHEAR FORCE ALONG VERTICAL PLANES
### Table 4: Dair Dam - Comparison Between Potential Shear Strength and Shear Force Along Vertical Planes

<table>
<thead>
<tr>
<th>Factor of Safety $F$</th>
<th>Slice No.</th>
<th>Potential Shear Strength Along Vertical Plane $S_v$</th>
<th>Vertical Shear Force $X_m$</th>
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<tr>
<td></td>
<td></td>
<td>$c'h + \left(\frac{E_1 + E_2}{2} - uh\right) \tan \phi'$</td>
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### Table 5: Folkestone Warren 1940 Landslip - Comparison Between Potential Shear Strength and Shear Force Along Vertical Planes

<table>
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<tr>
<th>Factor of Safety $F$</th>
<th>Slice No.</th>
<th>Potential Shear Strength Along Vertical Plane $S_v$</th>
<th>Vertical Shear Force $X_m$</th>
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TABLE 4: DAIR DAM - COMPARISON BETWEEN POTENTIAL SHEAR STRENGTH AND SHEAR FORCE ALONG VERTICAL PLANES

TABLE 5: FOLKESTONE WARREN 1940 LANDSLIP - COMPARISON BETWEEN POTENTIAL SHEAR STRENGTH AND SHEAR FORCE ALONG VERTICAL PLANES
parameters, the safety factor $F$ varies linearly with the pore pressure ratio $r_u$ - fig. 16. This is found to be true for the practical range of $r_u$ between 0 and 0.7 as stated by Bishop and Morgenstern (9). This relationship could be stated as:

$$F = A + Br_u$$

where $A$ and $B$ are the stability coefficients for the particular slope and soil properties; $A$ gives the value of $F$ when $r_u = 0$ and $B$ is the slope of the graph of $F$ plotted against $r_u$.

2. For the case considered the safety factor is found to vary linearly with the soil cohesion $c'$ - fig. 20.

3. As shown in table 10 the number of slices within the slip surface is found to have no appreciable effect on the factor of safety provided at least 7 slices are included.

4. Factors of safety calculated by the three different methods discussed in chapter 2 come close to each other as the angle of internal friction $\phi$ diminishes - fig. 18.

5. As mentioned by Bishop and Morgenstern (9), the position of the critical circle is more sensitive to change in the angle of slope than to any of the other variables involved in the calculation - Table 10.

6. In all cases considered, the values of $F$ calculated by Bishop's simplified method and the rigorous method are found to be/
found to be very close to each other. On the other hand, as pointed out by Bishop, the neglect of the side forces or the assumption that their resultant acts parallel to slip surface leads to an underestimate of the factor of safety. Moreover, the conventional and Bishop's simplified methods in most cases do not lead to the same critical circle, while the latter and the rigorous method often lead to the same critical circle.

4.4 APPLICATION TO EXISTING SLOPES

To compare the results obtained by using the previously described computer program and those obtained elsewhere by other methods, two cases are analysed:

1. Deer Dam : Fig. 14:

The analysis is based on the circular slip surface. The results obtained by Bishop (7) and those obtained by the Author's computer method are given in Table 11.

2. Folkestone Warren 1940 Landslip : Fig. 15:

Hutchinson's analysis, which was carried out after the slip had taken place, was based on a non-circular slip surface (10). The computer method applied to this case is based on a circular slip surface assumption which is chosen to be roughly coincident with the non-circular slip surface. The results obtained by the two different approaches are given in Table 12.

The factors of safety obtained for these earth slopes show reasonable agreement between the methods adopted in this thesis and other stability analysis methods.
<table>
<thead>
<tr>
<th>Fore Pressure ratio $r_u$</th>
<th>Conventional Method</th>
<th>Bishop's Simplified Method</th>
<th>Bishop's Rigorous Method</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Critical Circle</td>
<td>Critical Circle</td>
<td>Critical Circle</td>
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<tr>
<td></td>
<td>Factor of Safety $F$</td>
<td>Factor of Safety $F$</td>
<td>Factor of Safety $F$</td>
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<tr>
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<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
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<td>Radius (ft.)</td>
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</table>

**TABLE 6: EXAMPLE 1 - EFFECT OF VARYING $r_u$**
<table>
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<th>Angle of Slope $\beta$</th>
<th>Conventional Method</th>
<th>Bishop's Simplified Method</th>
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<td>40</td>
<td>1.293</td>
<td>10</td>
<td>65</td>
</tr>
<tr>
<td>45</td>
<td>1.106</td>
<td>0</td>
<td>75</td>
</tr>
</tbody>
</table>

**TABLE 7: EXAMPLE 2 - EFFECT OF VARYING ANGLE OF SLOPE**
<table>
<thead>
<tr>
<th>Angle of Internal Friction $\phi$</th>
<th>Conventional Method</th>
<th>Bishop's Simplified Method</th>
<th>Bishop's Rigorous Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Circle</td>
<td>Critical Circle</td>
<td>Critical Circle</td>
<td></td>
</tr>
<tr>
<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
<td></td>
</tr>
<tr>
<td>Radius (ft.)</td>
<td>Radius (ft.)</td>
<td>Radius (ft.)</td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td>$F$</td>
<td>$F$</td>
<td>$F$</td>
</tr>
<tr>
<td>$X_C$</td>
<td>$X_C$</td>
<td>$X_C$</td>
<td>$X_C$</td>
</tr>
<tr>
<td>$Y_C$</td>
<td>$Y_C$</td>
<td>$Y_C$</td>
<td>$Y_C$</td>
</tr>
<tr>
<td>6</td>
<td>0.885</td>
<td>0.915</td>
<td>0.912</td>
</tr>
<tr>
<td>20</td>
<td>1.069</td>
<td>1.198</td>
<td>1.194</td>
</tr>
<tr>
<td>30</td>
<td>1.198</td>
<td>1.379</td>
<td>1.379</td>
</tr>
<tr>
<td>37.5</td>
<td>1.313</td>
<td>1.540</td>
<td>1.546</td>
</tr>
<tr>
<td>45</td>
<td>1.439</td>
<td>1.737</td>
<td>1.745</td>
</tr>
<tr>
<td>60</td>
<td>1.746</td>
<td>2.262</td>
<td>2.291</td>
</tr>
</tbody>
</table>

**TABLE 8: EXAMPLE 3 - EFFECT OF VARYING**

<table>
<thead>
<tr>
<th>Soil cohesion $c'$ (lb/ft$^2$)</th>
<th>Conventional Method</th>
<th>Bishop's Simplified Method</th>
<th>Bishop's Rigorous Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Circle</td>
<td>Critical Circle</td>
<td>Critical Circle</td>
<td></td>
</tr>
<tr>
<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
<td>Co-ordinates of centre $X_C$</td>
<td></td>
</tr>
<tr>
<td>Radius (ft.)</td>
<td>Radius (ft.)</td>
<td>Radius (ft.)</td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td>$F$</td>
<td>$F$</td>
<td>$F$</td>
</tr>
<tr>
<td>$X_C$</td>
<td>$X_C$</td>
<td>$X_C$</td>
<td>$X_C$</td>
</tr>
<tr>
<td>$Y_C$</td>
<td>$Y_C$</td>
<td>$Y_C$</td>
<td>$Y_C$</td>
</tr>
<tr>
<td>0</td>
<td>0.288</td>
<td>0.322</td>
<td>0.333</td>
</tr>
<tr>
<td>40</td>
<td>0.447</td>
<td>0.598</td>
<td>0.609</td>
</tr>
<tr>
<td>60</td>
<td>0.526</td>
<td>0.677</td>
<td>0.691</td>
</tr>
<tr>
<td>80</td>
<td>0.601</td>
<td>0.750</td>
<td>0.760</td>
</tr>
<tr>
<td>100</td>
<td>0.669</td>
<td>0.822</td>
<td>0.829</td>
</tr>
<tr>
<td>120</td>
<td>0.736</td>
<td>0.893</td>
<td>0.898</td>
</tr>
<tr>
<td>150</td>
<td>0.837</td>
<td>0.998</td>
<td>1.003</td>
</tr>
<tr>
<td>200</td>
<td>1.002</td>
<td>1.152</td>
<td>1.159</td>
</tr>
<tr>
<td>250</td>
<td>1.156</td>
<td>1.302</td>
<td>1.309</td>
</tr>
<tr>
<td>300</td>
<td>1.296</td>
<td>1.476</td>
<td>1.479</td>
</tr>
<tr>
<td>350</td>
<td>1.437</td>
<td>1.597</td>
<td>1.594</td>
</tr>
<tr>
<td>Factor of Safety F</td>
<td>Conventional Method</td>
<td>Bishop's Simplified Method</td>
<td>Bishop's Rigorous Method</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
<td>---------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>Critical Circle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of slices within slip surface</td>
<td>Co-ordinates of centre</td>
<td>Radius (ft.)</td>
<td>No. of slices within slip surface</td>
</tr>
<tr>
<td>0.809</td>
<td>65</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>0.809</td>
<td>39</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>0.805</td>
<td>26</td>
<td>4.5</td>
<td>30</td>
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<tr>
<td>0.800</td>
<td>15</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>0.809</td>
<td>10</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>0.813</td>
<td>7</td>
<td>4.5</td>
<td>35</td>
</tr>
<tr>
<td>0.845</td>
<td>4</td>
<td>4.0</td>
<td>35</td>
</tr>
</tbody>
</table>

**TABLE 10: EXAMPLE 5 - EFFECT OF VARYING NUMBER OF SLICES**
### RESULTS OF COMPUTER ANALYSIS

<table>
<thead>
<tr>
<th>Method</th>
<th>Critical Circle</th>
<th>Critical Circle</th>
<th>Critical Circle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factor of Safety</td>
<td>Co-ordinates of Centre</td>
<td>Radius (ft.)</td>
</tr>
<tr>
<td></td>
<td>Xc</td>
<td>Yc</td>
<td></td>
</tr>
<tr>
<td>Conventional Method</td>
<td>1.393</td>
<td>300</td>
<td>380</td>
</tr>
<tr>
<td>Bishop's Simplified Method</td>
<td>1.512</td>
<td>360</td>
<td>510</td>
</tr>
<tr>
<td>Bishop's Rigorous Method</td>
<td>1.517</td>
<td>360</td>
<td>510</td>
</tr>
</tbody>
</table>

**TABLE 11: DIER EARTH DAM**

### RESULTS OBTAINED BY OTHER METHODS

<table>
<thead>
<tr>
<th>Method</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Method</td>
<td>1.58</td>
</tr>
<tr>
<td>Bishop's Simplified Method</td>
<td>1.53</td>
</tr>
<tr>
<td>Bishop's Rigorous Method</td>
<td>1.60</td>
</tr>
</tbody>
</table>

### RESULTS OF COMPUTER ANALYSIS

<table>
<thead>
<tr>
<th>Method</th>
<th>Critical Circle</th>
<th>Critical Circle</th>
<th>Critical Circle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factor of Safety</td>
<td>Co-ordinates of Centre</td>
<td>Radius (ft.)</td>
</tr>
<tr>
<td></td>
<td>Xc</td>
<td>Yc</td>
<td></td>
</tr>
<tr>
<td>Conventional Method</td>
<td>0.691</td>
<td>285</td>
<td>295</td>
</tr>
<tr>
<td>Bishop's Simplified Method</td>
<td>0.876</td>
<td>285</td>
<td>300</td>
</tr>
<tr>
<td>Bishop's Rigorous Method</td>
<td>0.884</td>
<td>285</td>
<td>300</td>
</tr>
</tbody>
</table>

**TABLE 12: FOLKESTONE WAREH 1940 LANDSLIP**
FIG. 16: RELATIONSHIP BETWEEN FACTOR OF SAFETY AND PORE PRESSURE RATIO

EXAMPLE 1

CONVENTIONAL METHOD
BISHOP'S SIMPLIFIED METHOD
BISHOP'S RIGOROUS METHOD
FIGURE 17: EXAMPLE 2—RELATIONSHIP BETWEEN FACTOR OF SAFETY AND ANGLE OF SLOPE
FIG. 18: EXAMPLE 3—RELATIONSHIP BETWEEN FACTOR OF SAFETY AND ANGLE OF SHEARING RESISTANCE
CONVENTIONAL METHOD

BISHOP'S SIMPLIFIED AND RIGOROUS METHODS

FIG. 19: EXAMPLE 3—RELATIONSHIP BETWEEN FACTOR OF SAFETY AND TAN $\phi$
FIG. 20: EXAMPLE 4—RELATIONSHIP BETWEEN FACTOR OF SAFETY AND SOIL COHESION $c'$

- Conventional Method
- Bishop's Simplified and Rigorous Method
CHAPTER 5

THE USE OF AN INTERACTIVE GRAPHICAL DISPLAY

FOR DESIGN OF EARTH DAMS

5.1 GENERAL

It has been found that most of the delay associated with the design of an earth dam by the digital computer is due to two main reasons:

1. After sending the proposed design to the computer unit, there is typically 2-day delay in getting analysis of the initial design.

2. The way in which these results are usually printed out by the computer requires careful study by the engineer to pick out the critical circle and the minimum factor of safety. Each time the design is revised a further 2-3 day delay occurs.

   The first of these might be overcome by having an on-line terminal although the usual teletype output might seem rather slow.

   The second can be overcome with the interactive graphical display system. This system allows the designer to study the slope design displayed on a screen in front of him and to consider different possible failure surfaces according to the output received by him in printed or graphical form, and, if necessary, modify his original design and call for the display of the new cross-section and recalculation.
5.2 HARDWARE SPECIFICATIONS

The diagramatic sketch shown in fig. (21) shows the interconnections of the following main features of the system:

1. The 4130 Elliott computer consists mainly of the tape reader and the line printer. The main computer program has to be compiled first by running through the paper tape reader (fig 22).

2. The PDP-7 computer, which is linked with the 4130 computer, is interconnected with a teletype which can be used by the designer when considering different possible designs.

3. Graphical display Cathode-ray tube of working area 9.375 x 9.375 inch. This is linked with the PDP-7 to transfer information in both directions.

4. Calcomp Drum Plotter is also interconnected with the PDP-7 and can be used to plot on paper the shape displayed on the screen.

5.3 SOLAR SYSTEM

The 'Solar' system is a software package which can be used in conjunction with Fortran programs to enable the designer to interact with the - 4130 computer and graphical display system (fig. 23).

Two main facilities are provided by this system:

1. The display of the cross-section of the earth slope on the screen makes the judgment of the designer and consideration/
consideration of alternative designs easier.

2. By adding special subroutines to the original Fortran slope stability analysis program, the designer can interact with the computer by using the PDP-7 teletype keyboard to input new values for any variable whose current value is previously output on the PDP-7 teletype.

The Fortran program used previously with the digital computer is modified to be used with "Solar system" - see appendix (7). In much the same way as before, the co-ordinates defining the geometry of the slope cross-section, the soil properties and the data for the first circle are present to the computer from the data tape. At first the original slope cross-section and the contours defining the different soil zones together with the first assumed slip circle are displayed on the screen. The value of the factor of safety F for that particular circle is then output on the PDP-7 teletype. Other possible slip surfaces can then be tried either by shifting the circle centre or by changing the Y-co-ordinate of the lowest tangent.

5.3.1 Shift of Centre

According to the appropriate instruction included in the computer program, a certain updated value for F (in this case less than 200) typed on the PDP-7 teletype will cause the current X and Y co-ordinates of the centre of the displayed circle to be output on the same teletype. The designer may then type in updated values for the X and Y co-ordinates defining the centre of the next circle to be analysed, and instantly the new/
instantly the new circle will be displayed and the current value of \( F \) corresponding to it is output on the PDP-7 teletype. The above procedure can be repeated for the different possible slip circles which are chosen according to the values of \( F \) output by the teletype in front of the designer.

5.2.2 Shift of Lowest Tangent

If, on the other hand, the lowest level which all circles should touch is to be shifted, another updated value for \( F \) (in this case: 200) should be typed and accordingly the current \( Y \)-co-ordinate of the last displayed tangent will be output on the PDP-7 teletype. Judging from the figure in front of him and the values of \( F \) output so far, the designer can change the level of the lowest tangent by typing an updated value on the same keyboard.

5.2.3 Alternative Design for the Slope

If the design is to be modified by changing the cross-section of the earth slope and/or the properties of some or all of the soils forming the slope, the updated value input for \( F \) should be greater than 200 in this case. This will keep the computer ready to receive new values which can be assigned to the shape of the slope or the soil properties.

If, for instance, the position of the top contour of the slope shown in fig. 24 is to be changed by shifting point \( B \) to \( B' \) as shown dotted, the number of the contour and the number of the point to be shifted are typed on the PDP-7 teletype keyboard. Immediately after this the current values of the \( X \) and \( Y \)
and Y co-ordinates of that particular point are output by the
teletype and the machine will be waiting for the updated values
which are then assigned to that point. If further changes are
desired, the same process may be repeated.

A similar procedure can be followed if the property of
any soil is to be changed. This can be achieved by typing the
number of the soil and the number of the property to be changed
before giving the updated desired value of that property which
will then be received back by the computer.

Finally the computer, obeying certain instructions
included in the program, stores the new values, displays the
resulting cross-section and repeats all the necessary calculations
to find the safety factor F for the new modified design.

5.3.4. Advantages

The advantages gained by using this system can be summarised
in the following points:

1. Judging from the output typed beside him and the
displayed slope cross-section, the designer can easily
see whether he needs to consider an alternative design
for the slope by changing its geometry or not.

2. Similarly the soils forming the slope can be replaced
by some other soils with different properties, and even
more important, the pore pressure distribution, which
has a great effect on the factor of safety, can be
examined and possible alternative distributions can
be considered.
3. With the benefit of the graphical display the designer is no longer likely to try certain slip circles which would not satisfy the conditions stated in chapter 3 or circles far from the critical circle giving the minimum factor of safety for the slope considered; thus saving both the designer’s and computer’s time.

The 'Solar system', however, seems to involve a lot of typing on the connected teletype to specify every change required either for the slip circle or the design itself. Although the design time is clearly shortened by using the solar system for the stability analysis yet, further development of the techniques involving direct communication between the engineer and the computer can be achieved by using the new "Spindle System".

5.4 SPINDLE SYSTEM

This is a new system which is an extension of the solar system (13). It provides the facility of using the Light Pen when considering different slip surfaces or alternative designs for the slope. The Light Pen Interaction is introduced by adding some new subprograms to the previous computer program used with the solar system.

5.4.1 Light Pen

The Light Pen is an interactive device which consists of a holder containing a phot electric cell connected to the computer (14). According to certain subroutines in the computer program, part or all of the displayed picture may be made sensitive.
made sensitive to the Light Pen. The existing position of any point on such a display may be changed by pointing the Light Pen at the point and then moving the Light Pen to the new desired position while pressing the trigger on its side. This will cause the point to shift to the new position. The Light Pen may also be used to shift the position of the tracking cross, which is usually displayed with the picture, to any desired position and automatically the X and Y coordinates of the new position of the tracking cross will be received by the computer. In such a way the complete display can be changed and a new one may be built up instead. By typing the appropriate characters on the PDP-7 keyboard, the computer will assign the current position of the tracking cross to the corresponding variable indicated in the computer program.

5.4.2 Display of Safety Factor

In addition to the above mentioned facilities, the introduction of certain subprograms to the computer program makes it possible to have the current value of safety factor F displayed at the top of the slope cross-section. Thus for every assumed slip circle, the factor of safety is output in front of the designer who can accordingly make the necessary modifications to his original design.

5.4.3 Shift of Slip Circle

The tracking cross is initially displayed at the centre of the first assumed circle whose data is presented to the computer together with the original proposed slope design. The factor of safety/
factor of safety for that particular circle is also displayed on the screen. To consider the next possible slip circle, the tracking cross can be moved by the Light Pen to the position of the centre of the new circle. If the appropriate character (in this case : 0) is typed on the PDP-7 keyboard, the X and Y co-ordinates of the current position of the tracking cross will be returned to the computer and assigned to the X and Y co-ordinates of the circle centre respectively. Following this, the previous slip circle disappears and the new one is displayed together with the new calculated factor of safety. At this stage the tracking cross, which represents the circle centre, can be shifted by the Light Pen to any position on the screen and accordingly the value of F corresponding to each centre is displayed. Judging from the values given for F, the centre can be moved to the position where it is likely to give the critical circle with that particular lowest tangent.

In the mean time if the results of calculations for any slip circle are required in typed form, the input of the letter P on the PDP-7 keyboard will cause the print out of these results by the line printer - fig. (5). On the other hand, if more changes other than the centre of the circle are desired, the input of the letter X will cause the computer to go out of this circle mode and to wait for a new message about the next shift of the tracking cross.

5.4.4 Shift of Lowest Tangent

In a similar way this can be done by shifting the tracking cross to/
cross to the desired position of the lowest tangent and typing the letter T on the keyboard. To try some other slip circles with this new tangent, the circle mode is entered again by typing the letter O and the previous procedure can be repeated for any number of possible slip circles.

5.4.5 Modification of the Design

Sometimes it might be desirable, according to the results output when analysing a particular earth slope, to modify the design by changing the slope cross-section to a more reasonable one. To achieve this all points on the different contours are first made sensitive to Light Pen by including certain subroutines and statements in the computer program. The light pen is first pointed at the point to be shifted and then moved to the new required position to which the tracking cross is automatically shifted. The input of the letter B on the PDP-7 keyboard will cause the computer to, the current X and Y co-ordinates of the tracking cross and assign them to the corresponding co-ordinates of the new point on the cross-section. The input of the letter F after this will fix the new position, display the modified cross-section and call for recalculation of the factor of safety for the new slope design.

If, however, the earth slope is to be modified by changing the positions of more than one point on the cross section, the new point can be fixed by typing the letter M which also keeps the computer ready to receive new co-ordinates of the next shifted point. When all the desired points are shifted to their new/
their new positions, the letter X is input on the PDP-7 keyboard to call for recalculation and analysis of the modified design. It is also possible to restore the original co-ordinates of any one point at a time if, for any reason, the designer changes his mind about the new position he has chosen for that particular point.

It is sometimes desirable to know the exact profile of some or all the modified designs tried during the whole process. This can be achieved by including the appropriate statements in the computer program and accordingly the co-ordinates of any modified point on any of the contours are output by the line printer. In addition to this, the profile of the final design can be plotted by the Calcomp Drum Plotter which allows accurate hard copy diagrams to be obtained on line. A plotted copy of an earth-slope example chosen arbitrarily is shown in fig (25).

5.4.6 Advantages of Spindle System

In addition to the benefits gained by using the solar system, the spindle system has the following advantages:

1. The use of the Light Pen allows the designer to locate the modified position on the screen more accurately instead of typing estimated co-ordinates.

2. For a particular earth-slope displayed on the screen, many slip circles can be tried in a very short time by moving the centre about with the Light Pen.

3. The display of safety factor makes the process of finding the most critical circle quicker and easier as the/
as the positions of the circles can be chosen according to the observed values output for F.

4. The design time is shortened by avoiding a lot of the typing on the PDP-7 keyboard as only single characters are needed to define the significance of the position of the tracking cross. This makes the process of considering alternative designs quicker and consequently the design cost is reduced.
Fig. 21: Diagramatic Sketch for the Interconnections of the Interactive System
FIGURE 22: TAPE READER
FIGURE 23: GRAPHIC DISPLAY SYSTEM
FIG. 24: DESIGN MODIFICATION
FIG. 25: AN EARTH DAM CROSS-SECTION PLOTTED BY THE CALCOMP DRUM PLOTTER
CHAPTER 6

CONCLUSIONS

6.1 FACTOR OF SAFETY

6.1.1. Comparison Between Current Methods of Stability Analysis

Regarding the different methods used for the determination of the safety factor and from the results obtained for the cases considered in this thesis, the following conclusions are drawn:

1. The conventional method, though easy in application and not involving many calculations, gives a low value for F and consequently an uneconomical design. In some cases the value obtained for F by this method is only about half that obtained by the other more accurate methods.

2. Bishop's simplified method gives a value for F very close to that obtained by the rigorous method. The improvement by the latter method does not exceed 4% in the extreme case (usually about 1%). This suggests that for practical application in design of earth slopes, Bishop's simplified method is more suitable than the rigorous method in which many calculations and repetitive work is involved.

6.1.2. Effective Normal Stress

1. For some slices on the earth slope the effective normal force N' at their bases may have negative or zero values. This happens when the slice has the combination of either:
high pore pressure, small factor of safety and large angle $\theta$.

2. The introduction of the side forces to the problem increases the possibility of some slices having negative $N'$.

3. The frictional force, which should always act in a direction opposite to that of the forces causing failure, should always be limited to positive or zero values. Hence, it is recommended that the factor of safety of any earth slope should be determined by applying Bishop's simplified method together with the adjustment of $N'$ to zero for some slices where it is originally found to be negative.

6.2 PARAMETERS AFFECTING SAFETY FACTOR

The results obtained by the application of the computer method to homogeneous earth slope problems lead to the following conclusions:

1. Factor of safety of a simple earth slope varies linearly with the pore pressure ratio $r_u$.

2. It also varies linearly with the soil cohesion $c'$.

3. The number of slices within the slip surface has no serious effect on the factor of safety provided at least 7 are included.

4. The position of the critical circle is more sensitive to the change of angle of slope than to any of the other variables.
6.3 EXTERNAL FORCES

External applied forces on the slope surface are involved in the equilibrium of the individual slices within the sliding mass. This is justified by two main reasons:

1. Where a part of these forces acts on an individual slice, there is no justification for neglecting this part when considering the equilibrium of that particular slice.

2. If the external force is vertical it can be treated conveniently as an addition to the slice weight. In this case the pore pressure ratio $r_u$ involved in the calculation is given by:

$$r_u' = \frac{ub}{w'}$$

where: $w'$ = weight of the soil within the slice + the part of the vertical external force acting at the surface of that slice.

6.4 COMPUTER GRAPHICAL METHOD

6.4.1 Advantages

The advantages gained by the application of the interactive graphical display system to the stability analysis of earth slopes are summarised in the following points:

1. The display of earth slope cross-section and the use of Light Pen make the process of considering alternative designs much easier and quicker.

2./
2. The display of the factor of safety for each slip circle helps the designer to find the critical circle for the slope and to make the necessary modifications in a more efficient way.

3. The design time is shortened and accordingly the design cost is greatly reduced.

6.4.2 Future Developments

The following are some possible future developments which can be achieved by using the interactive graphical display system:

1. In the present computer method the co-ordinates of the earth slope cross-section which is initially displayed on the screen have to be presented to the computer from a data tape before the designer can interact with the computer and consider alternative possible designs. A possible development can be achieved if the designer can start the interaction with a blank screen on which the initial proposed slope cross-section can be built up with the Light Pen.

2. After considering various possible modifications for the design, the engineer might wish to return to his original cross-section as displayed initially on the screen. At present the co-ordinates of only the last shifted point can be restored at any time. It seems quite easy to modify the present computer program to allow for the restoration of the original cross-section whenever it is desired.
3. If the factor of safety can be displayed and kept on the screen at the centre of the corresponding slip circle, this might give the designer a clearer form of the variations in $F$ and accordingly he could find the position of the critical circle in a short time by choosing circles with centres round the minimum displayed value for $F$. 
REFERENCES


17. "Computer Applications in Civil Engineering" - Department of Civil Engineering, University of Strathclyde.


23. R.R. Chugaev: "Stability Analysis of Earth-Slopes".


25. A.W. Bishop: "The Stability of Earth Slopes" Ph.D. Thesis - University of London - 1952 (This thesis was requested from London University, but was not available before typing this thesis).
APPENDIX II

NOTATION FOR SLOPE STABILITY PROGRAM 707

\[
\begin{align*}
X_{\text{MIN}} & = \text{minimum } X \text{ co-ordinate specified} \\
X_{\text{MAX}} & = \text{maximum } X \text{ co-ordinate specified} \\
A & = \text{maximum width of slice specified} \\
N & = \text{no. of "contours"} \\
I & = \text{total no. of specified contour points} \\
T & = \text{total no. of slices in full cross-section} \\
I_{\text{MAX}} & = \text{maximum no. of points on any one contour} \\
N_{\text{TH}} & = \text{no. of points specified on } I-\text{th contour} \\
X(I) & = X \text{ co-ordinate of a specified contour point, stored in ascending order} \\
X(I) & = \text{specified } X \text{ co-ordinates + extra values to ensure maximum difference in } X = A, \text{ stored in ascending order.} \\
X(I) & = X(I + 1) - X(I) = \text{width of slice } (I). \\
A(I,J,K) & = \text{storage locations for } X \text{ and } Y \text{ co-ordinates of specified points on contour } I (I = 1 \text{ for top contour}). \\
J & = 1 \text{ for } X \text{ co-ordinate} \\
J & = 2 \text{ for } Y \text{ co-ordinate} \\
K & = \text{point no. on this contour, L.H. point } = 1 \\
X(1) & = X \text{ co-ordinate at middle of slice } (I) \\
Y(J,I) & = Y \text{ co-ordinate of contour } (J) \text{ at middle of slice } (I) \\
J & = 1 \text{ for top contour}; J = N \text{ for bottom contour}
\end{align*}
\]
\( \overline{w}(J,I) \) = weight of slice (I) down to contour (J)

\( S(J,K) \) = soil property in zone immediately below contour (J)

\( K = 1 \) for bulk density \( \gamma \)

\( K = 2 \) for \( c' \)

\( K = 3 \) for \( \tan \phi' \)

\( K = 4 \) for \( r_u \)

\( HT \) = \( Y \) co-ordinate of lowest horizontal tangent to a set of circles to be analysed

\( XC,YC \) = co-ordinates of the circle being analysed

\( R \) = radius of the circle being analysed

\( R^2 \) = \((R)^2\)

\( I \ \) FIRST = no. of first slice within circle considered

\( \) LAST = no. of last slice within circle considered

\( ISLIC \) = no. of slices whose mid-ordinate is cut by the circle considered

\( ZNC \) = no. of circle considered

\( \mathbf{W} I \) = wt. of a slice above the slip circle

\( \mathbf{SUMA} \) = \( \sum \{c' \cdot l + \tan \phi' (w \cos \theta - u)\} \), in equation (1.16)

\( \mathbf{SUMB} \) = \( \sum \) \( w \mathbf{x} \), in the original notations

\( \mathbf{TERM}_C(I) \) = \( \cos \theta \), where \( \theta \) is the angle made by base of slice (I) with the horizontal.

\( C(I) \) = \( Y \) co-ordinate of intersection of slip circle with mid-ordinate of a slice.

\( H \) = height of slice

\( \mathbf{AX} 1(I), \mathbf{AX} 2(I) \) = vertical side forces to the left and right of slice (I) respectively
TERMI(I) = $\tan \phi' \sin \theta$ in equation (1.18) for slice (I)
TERMT(I) = $\tan \theta$ in equation (1.20)
TERMX(I) = $(x_1 - x_2) \tan \phi'$ in equations (1.18) and (1.20)
TERME(I) = $w \tan \theta$ in equation (1.20)
TERMA(I) = $c'b + w(1 - r_u)\tan \phi'$ given by equation (1.18) after substituting $\frac{r_u w}{b}$ for $u$ and putting $(x_1 - x_2) = 0$ for every slice

$D = \cos \theta + \frac{\tan \phi' \sin \theta}{F}$ in equations (1.18) and (1.20)

SUMC = $\sum \left[ \frac{c'b + w(1 - r_u)\tan \phi'}{\cos \theta + \frac{\tan \phi' \sin \theta}{F}} \right]$ in equation (1.18) with $(x_1 - x_2) = 0$

AMAX(0) = Initial assumed maximum vertical side force at approximately the mid-ordinate of the sliding mass.
AMAX(L) = Final value of maximum vertical side force obtained after iteration, $L$ being the no. of iterations before reaching this value.
F(0) = Factor of safety by the Conventional Method
F(M) = Factor of safety by Bishop's Simplified Method
F(K1) = Factor of safety by Bishop's Rigorous Method.
APPENDIX III

BRIEF DESCRIPTION OF VARIOUS PARTS OF PROGRAM 707 (SPINDLE)

<table>
<thead>
<tr>
<th>PART</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>This part instructs the computer to read from the data tape the co-ordinates of all contours defining the slope cross-section and the soils' properties.</td>
</tr>
<tr>
<td>2</td>
<td>To divide the whole slope cross-section into vertical slices of a specified maximum width and to determine and store the total number of slices.</td>
</tr>
<tr>
<td>3</td>
<td>To store the X-co-ordinates of all specified points in ascending order (starting from left end to right end of the cross-section).</td>
</tr>
</tbody>
</table>
| 4    | This part instructs the computer to calculate and store:  
   a) The width of each slice.  
   b) The X co-ordinate of centre line of each slice.  
   c) The Y co-ordinate of the points of intersection of these centre lines with the different contours.  
   d) The weight of each slice. |
| 5    | This part contains the subroutines according to which the slope cross-section and the assumed slip circle are displayed on the screen. |
| 6    | This part allows for man-machine interaction by using the Light Pen and the PDP-7 Keyboard to shift the circle centre, the lowest tangent or to modify the slope cross section. |
This part is to determine:

a) The number of slices within the slip surface considered.

b) Y co-ordinate of the point of intersection of centre line of each slice with the slip surface.

c) The factor of safety according to the three methods discussed in chapter 2. It also checks whether the slip surface satisfies the conditions stated in chapter 3 or not.

This part is concerned with the display of the factor of safety (Bishop's Rigorous Method) on the screen together with the slip circle.

This part contains the statements according to which the results of the analysis are output in printed form by the line printer.
APPENDIX IV
PROGRAM 5CX

FOR CALCULATING FACTORS OF SAFETY ACCORDING TO THE THREE
METHODS DISCUSSED IN CHAPTER 2

&JOB;STABILITY ANALYSIS OF SLOPE 5CX;
&FORTRAN;

COMMON/HOLD1/N2
COMMON/HOLD2/N1,X1
COMMON/HOLD3/IA2,X
COMMON/HOLD4/I1
COMMON/HOLD5/N,A,IA1
DIMENSION IA1(7),X(50),X1(200),A(7,2,50)

417 READ(3,1200)XMIN
1200 FORMAT(F10.0)
   IF(XMIN.EQ.-9999.)GO TO 13
   READ(3,200)XMAX,AL,N
200 FORMAT(2F10.0,13)
   IF(N-5)17,17,21
21 STOP
17 IA2=0
1MAXA1=0
N2=N+2
DO 5 I=1,N2
   READ(3,300)IA1(I)
300 FORMAT(13)
   IA1(I)=NO. OF POINTS ON I-TH CONTOUR ,IA1(N+i)= NO. OF POINTS ON PIEZ. SURFACE ,IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
IA2=IA2+IA1(I)
5 CONTINUE
300 FORMAT(13)
   IA1(1)=NO. OF POINTS ON I-TH CONTOUR ,IA1(N+1)= NO. OF POINTS ON PIEZ. SURFACE ,IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
IA2=IA2+IA1(1)
C IA2=TOTAL NO. OF POINTS SPECIFIED
   IF(IA1(1)-IMAXA1)5,5,6
6 IMAXA1=IA1(1)
5 CONTINUE
   IF(IA2=50)4,4,3
3 STOP
4 IF(IMAXA1-50)2,2,3
2 N1=N+1
   DO 7 I=1,N1
      IL=IA1(I)
   DO 7 J=1,2
      7 READ(3,400)(A(I,J,K),X1,IL)
400 FORMAT(2X,7F10.0)
   C READS ALL X VALUES FOR ONE CONTOUR (INCL. PIEZO. SURFACE) FOLLOWED
C BY Y VALUES FOR THAT CONTOUR
ILA=IA1(N2)
   READ(3,228)(A(N2,1,K),K=1,ILA)
228 FORMAT(2X,7F10.0)
C READS X VALUES FOR SURCHARGE LIMITS
   CALL SOLVE
   X1(1)=XMIN
   I=2
   J=2
206 IF(X(I)-X(I-1))209,207,209
207  I=I+1
209  IF(X(1)-(X1(J-1)+AL))8,8,10
10  X1(J)=X1(J-1)+AL
   J=J+1
   GO TO 209
   8  X1(J)=X(1)
   IF(X1(J)-XMAX)11,12,11
11  I=I+1
   J=J+1
   GO TO 206
C ENSURES MAX. DIFF. IN X =AL AND NO X VALUE IS DUPLIC.
12  I1=J-1
C I1=TOTAL NO. OF SLICES IN FULL C.S.
11  WRITE(2,501)
   501 FORMAT(/)
   WRITE(2,500)I1
   500 FORMAT(35H TOTAL NO OF SLICES IN FULL C.S. = ,13//)
   IF(I1-200)14,13,13
14  CALL CALC
   CALL RESULT
   GO TO 417
13  STOP
END
SUBROUTINE SOLVE
COMMON/HOLD1/N2
COMMON/HOLD3/IA2,X
COMMON/HOLD5/N,A,IA1
COMMON/HOLD6/I1
DIMENSION IA1(7),X(50),A(7,2,50)
I1=IA1(1)
   DO 15 I=1,I1
15  X(I)=A(1,1,I)
   IPA=I1+1
   DO 16 I=IPA,IA2
16  X(I)=0
C STORES VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
   DO 18 I=2,N2
      M=1
      I1=IA1(I)
      DO 18 K=2,I1
18    M=M+1
      IF(A(1,1,K)-X(M))19,18,20
19    J=IA2
22  X(J)=X(J-1)
      J=J-1
      IF(J-(M+1))178,22,22
22    X(M)=A(1,1,K)
18   CONTINUE
C INSERTS OTHER X COORD. IN APPROPRIATE POSITIONS
RETURN
END
SUBROUTINE CALC
COMMON/HOLD2/N1,X1
COMMON/HOLD3/IA2,X
COMMON/HOLD4/I1
COMMON/HOLD5/N,A,IA1
COMMON/HOLD7/DX,X2,Y,NM,S,W
DIMENSION IP(6),DX(200),X2(200),X1(200),Y(6,200),W(5,200),
1S(4,4),SUR(4),A(7,2,50),IA1(7),X(50)
IF(IA1(N+2)-5)451,451,452
452 STOP
451 DO 23 I=1,II
   DX(I)=X1(I+1)-X1(I)
23 X2(I)=(X1(I)+X1(I+1))*0.5
C X2(I)=X COORD. AT MIDDLE OF SLICE (I)
   DO 24 J=1,N1
      IP(J)=1
      K=IP(J)
   DO 24 I=1,II
      IF(X2(I)-A(J,1,K+1))24,24,25
   25 K=K+1
   IF(A(J,1,K+1)-A(J,1,K))24,271,24
271 K=K+1
   24 Y(J,I)=A(J,2,K)+(A(J,2,K+1)-A(J,2,K))*(X2(I)-A(J,1,K))/
      (A(J,1,K+1)-A(J,1,K))
   C Y(J,I)=Y COORD. OF CONTOUR (J) AT MIDDLE OF SLICE (I)
   ITN=IA1(N+2)-1
   READ(3,226)(SUR(M),M=1,ITN)
226 FORMAT(2X,7F10.0)
   C SUR(M)=SURCHARGE TO RIGHT OF POINT A(N+2,1,M)
   NM=N-1
   DO 26 J=1,NM
      26 READ(3,600)(S(J,K),K=1,4)
600 FORMAT(2X,4F10.0)
   C S(J,K)=SOIL PROPERTY BELOW CONTOUR (J) AND TOP CONTOUR IS J=1,
   C K=1 FOR DENSITY, K=2 FOR COHESION, K=3 FOR FRICTION (TAN), K=4 FOR RU
   M=1
   DO 27 I=1,II
      IF(X2(I)-A(N+2,1,M+1))591,591,592
   592 M=M+1
591 W(1,I)=DX(I)*SUR(M)
   DO 27 J=1,NM
      27 W(J+1,I)=W(J,I)+DX(I)*(Y(J,I)-Y(J+1,I))*S(J,1)
   C W(J,I)=WT. OF SLICE (I) DOWN TO CONTOUR (J)
   RETURN
END
SUBROUTINE RESULT
COMMON/HOLD4/II
COMMON/HOLD5/N,A,IA1
COMMON/HOLD6/II
COMMON/HOLD7/DX,X2,Y,NM,S,W
DIMENSION C(200),TERMA(200),TERMC(200),TERMD(200),F(40),X2(200),
1DX(200),Y(6,200),W(5,200),S(4,4),A(7,2,50),AMAX(40),AX1(200),
2AX2(200),XNET(200),TERMT(200),TERMX(200),TERMB(200),IA1(7)
WRITE(2,222)
222 FORMAT(72H NO. 	 HT 	 XC 	 YC SLICES F(0) 	 F(M) 	 M F(K1
1) K1 COMMENT//)
   ZNC=0.
679 READ(3,508)HT
508 FORMAT(F10.0)
   IF(HT,LT,0.)RETURN
   READ(3,3131)NX1,NX2,NDX,NY1,NY2,NDY
3131 FORMAT(6I5)
   DO 37 MY=NY1,NY2,NDY
   YC=MY
   R=YC-HT
   R2=R*R
   DO 37 MX=NX1,NX2,NDX
   XC=MX
   ZNC=ZNC+1.
   IFIRST=0
   LAST=()
   DO 39 I=1,II
   IF(ABS(XC-X2(I))-R)38,38,39
   38 C(I)=YC-SQRT(R2-(XC-X2(I))*(XC-X2(I)))
   IF(C(I)-Y(1,I))40,42,42
   40 LAST=I
   IF(IFIRST)42,41,42
   IFIRST=I
   42 IF(C(I)-Y(N,I))43,39,39
   39 CONTINUE
   C IFIRST(LAST)=NO. OF FIRST(LAST) SLICE WITHIN THE CIRCLE
      IF(IFIRST)45,44,45
      44 IF(LAST)45,46,45
      45 IF(Y(1,IFIRST)-YC)47,47,48
      47 IF(Y(1,LAST)-YC)49,49,48
      49 ISLIC=LAST-IFIRST+1
      C ISLIC=NO. OF SLICES WHOSE MID-ORDINATE IS CUT BY THE CIRCLE CONSIDERED
      IF(ISLIC-3)50,50,51
      51 IF(IFIRST-1)53,52,53
      52 IF(LAST-I)55,54,55
      C PROCEED WITH ANALYSIS OF THIS CIRCLE
      55 CENTRE=(X2(LAST)+DX(LAST)/2.+X2(IFIRST)+DX(IFIRST)/2.)/2.
      DO 602 I=IFIRST,LAST
         IF(CENTRE-X2(I))603,601,602
      602 CONTINUE
      603 IF(ABS(CENTRE-X2(I))-(CENTRE-X2(I-I)))601,601,605
      601 CENTRE=X2(I)
         H=Y(1,I)-C(I)
         GO TO 607
      605 CENTRE=X2(I-1)
         H=Y(1,I-1)-C(I-1)
      607 FACTOR=5.
         CONST1=X2(IFIRST)+DX(IFIRST)/2.
         CONST2=X2(LAST)+DX(LAST)/2.
         SUMA=0.
         SUMB=0.
         DO 60 I=IFIRST,LAST
            IF(C(I)-Y(1,I))57,56,56
         57 DIST1=X2(I)-DX(I)/2.-CONST1
            IF(DIST1+CONST1-CENTRE)391,391,392
      391 AX1(I)=DIST1/(CENTRE-CONST1)
            GO TO 301
      392 AX1(I)=(CONST2-(DIST1+CONST1))/(CONST2-CENTRE)
      301 DIST2=X2(I)+DX(I)/2.-CONST1
         IF(DIST2+CONST1-CENTRE)393,393,394
      393 AX2(I)=DIST2/(CENTRE-CONST1)
            GO TO 308
      394 AX2(I)=(CONST2-(DIST2+CONST1))/(CONST2-CENTRE)
XNET(I)=AX(I)-AX2(I)

DO 58 J=1,NM
  IF(C(I)-Y(J+1,1))58,58,59
58 CONTINUE

59 W1=W(J,1)+(Y(J,1)-C(I))*DX(I)*S(J,1)
  TERMCI(I)=(YC-C(I))/R
  TERMD(I)=S(J,3)*(XC-X2(I))/R
  TERMT(I)=(XC-X2(I))/(YC-C(I))
  TERMX(I)=XNET(I)*S(J,3)
  TERME(I)=W1*TERMT(I)
  IF(S(J,4)+1.)81,82,81
81 TERMCI(I)=S(J,2)*DX(I)+S(J,3)*W1*(1-S(J,4))
  SUMA=SUMA+S(J,2)*DX(I)/TERMC(I)+S(J,3)*W1*(TERMCI(I)-S(J,4))/
     TERMCI(I))
  GO TO 60
82 U=62.4*(Y(N+1,1)-C(I))
  IF(U)83,84,84
83 U=0.
84 TERMCI(I)=S(J,2)*DX(I)+S(J,3)*(W1-U*DX(I))
  SUMA=SUMA+S(J,2)*DX(I)/TERMC(I)+S(J,3)*(W1*TERMCI(I)-U*DX(I))/
     TERMCI(I))
60 SUMB=SUMB+W1*(XC-X2(I))

C SUMB IS +VE IF CENTROID TO L. OF CENTRE
  SUMB=SUMB/R
  IF(SUMB)86,85,85
86 DO 87 I=IFIRST,LAST
    TERMCI(I)=-TERMT(I)
    TERMX(I)=-TERMCI(I)
    TERMD(I)=-TERMD(I)
87 SUMR=-SUMB
C CENTROID TO R. OF CENTRE
85 F(K1)=SUMA/SUMB
C NEGLECTS FORCES BETWEEN SLICES
89 K1=1,20
DO 88 I=IFIRST,LAST
  SUMC=0.
  SUMD=0.
  DO 88 I=IFIRST,LAST
    D=TERMCI(I)*F(K1-1)+TERMD(I)
    SUMC=SUMC+TERMCI(I)*D
    SUMD=SUMD+TERMCI(I)*D
88 F(K1)=F(K1-1)*(1-(SUMB-SUMC)/(SUMB-SUMD))
  IF(ABS(F(K1)-F(K1-1))<0.005)91,89,89
91 CONTINUE
WRITE(2,130)ZN.C,HT,XC,YC,ISLIC,F(0),F(K1),K1
130 FORMAT(F5.0,1H 3(F4.0,2X),13,3H 	 ,F6.3,2H ,F6.3,2H ,I3,40H
1 ITERATION UNSATISFACTORY/)
GO TO 37
91 F(K1)=F(K1)
M=K1
919 AMAX(0)=FACTOR*H*H
L=0
908 L1=L+1
L2=L+20
DO 821 L=L1,L2
  SUMNUM=0.
  SUMDEN=0.
  DO 411 I=IFIRST,LAST
    D1=TERMCI(I)*(TERMCI(I)*F(K1)+TERMD(I))
SUMNUM=SUMNUM+((TERMA(I)+AMAX(L-1)*TERMX(I))/D1-TERME(I)-AMAX(L-1))
1+XNET(I)*TERMT(I)
411 SUMDEN=SUMDEN+TERMX(I)/D1-XNET(I)*TERMT(I)
AMAX(L)=AMAX(L-1)-SUMNUM/SUMDEN
IF(ABS(AMAX(L)-AMAX(L-1))-0.005)812,821,821
821 CONTINUE
WRITE(2,170)ZNC,HT,XC,YC,ISLIC,F(0),F(M),M
170 FORMAT(F5.0,1H ,3(F4.0,2X),13,3H ,F6.3,2H ,F6.3,2H ,13)
WRITE(2,171)AMAX(0),AMAX(L),L,FACTOR
171 FORMAT(9H AMAX(0)=,F7.0,9H AMAX(L)=,F7.0,3H L=13,8H FACTOR=,F4.0,
12H AMAX(0) NOT SUITABLE//)
FACTOR=FACTOR+1.
GO TO 919
812 K2=K1+1
K3=K1+20
DO 902 K1=K2,K3
SUMC1=0.
SUMD1=0.
DO 903 I=IFIRST,LAST
G1=TERMA(I)+AMAX(L)*TERMX(I)
D2=TERMC(I)*F(X1.-1)+TERMD(I)
S1JC1=SUMC1+G1/D2
903 SUMD1=SUMD1+G1*TERMD(I)/(D2*D2)
F(K1)=F(K1-1)*(1.-(SUMB-SUMC)/SUMB-suMD1))
IF(ABS(F(K1)-F(K1-1))-0.005)904,902,902
902 CONTINUE
GO TO 908
904 IF(K1.GT. K2)GO TO 908
WRITE(2,214)ZNC,HT,XC,YC,ISLIC,F(0),F(M),M,F(K1),K1
214 FORMAT(F5.0,1H ,3(F4.0,2X),13,3H ,F6.3,2H ,F6.3,2H ,13)
WRITE(2,196)AMAX(0),AMAX(L),L,FACTOR
196 FORMAT(9H AMAX(0)=,F7.0,9H AMAX(L)=,F7.0,3H L=13,8H FACTOR=,F4.0/
1/)
GO TO 37
C CONSIDER NEXT CIRCLE
43 WRITE(2,350)ZNC,HT,XC,YC
350 FORMAT(F5.0,1H ,3(F4.0,2X),67H
1 CIRCLE CUTS BOTTOM CONTOUR//
GO TO 37
46 WRITE(2,450)ZNC,HT,XC,YC
450 FORMAT(F5.0,1H ,3(F4.0,2X),58H
1 CIRCLE DOESNT CUT//
GO TO 37
48 WRITE(2,550)ZNC,HT,XC,YC
550 FORMAT(F5.0,1H ,3(F4.0,2X),75H
1 TOP CONTOUR CUTS UPPER SEMI CIRCLE//
GO TO 37
50 WRITE(2,650)ZNC,HT,XC,YC,ISLIC
650 FORMAT(F5.0,1H ,3(F4.0,2X),I3,52H
1 TOO FEW SLICES//
GO TO 37
52 C(I1+1)=Yc-SQR(R2-*XC*Xc)
IF(C(I1+1)=A(1,2,1))61,53,53
61 WRITE(2,750)ZNC,HT,XC,YC,ISLIC
750 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H
1 CIRCLE CUTS L.H. EDGE/
GO TO 37
54 C(I1+1)=YC-SQRT(R2-(X2(I1)-XC+DX(I1)*0.5)*(X2(I1)-XC+DX(I1)*0.5))
IF(C(I1+1)-A(1,2,1L1))62,55,55
62 WRITE(2,850)ZNC,HT,XC,YC,ISLIC
850 FORMAT(F5.0,1H ,3(F4.0,2X),13,59H
1 CIRCLE CUTS R.H. EDGE/
GO TO 37
56 WRITE(2,950)ZNC,HT,XC,YC,ISLIC
950 FORMAT(F5.0,1H ,3(F4.0,2X),13,55H
1 CIRCLE CUTS TWICE/
37 CONTINUE
GO TO 679
RETURN
END
&RUN;
APPENDIX V

PROGRAM 598XX

FOR CALCULATING FACTORS OF SAFETY ACCORDING TO THE THREE
METHODS WITH THE ADJUSTMENT OF SOIL FRICTIONAL FORCE TO
POSITIVE OR ZERO VALUES

&JOB;STABILITY ANALYSIS OF SLOPE 598XX;
&FORTRAN;

COMMON/HOLD1/N2
COMMON/HOLD2/N1,X1
COMMON/HOLD3/IA2,X
COMMON/HOLD4/I1
COMMON/HOLD5/N,A,IA1
DIMENSION IA1(7),X(50),X1(200),A(7,2,50)
417 READ(3,1200)XMIN
1200 FORMAT(F10.0)
    IF(XMIN.EQ.-9999.)GO TO 13
    READ(3,200)XMAX,AL,N
200 FORMAT(2F10.0,13)
    IF(N-5)17, 17,21
17 IA2=0
    IMAXA1=0
    N2=N+2
    DO 5 I=1,N2
        READ(3,300)IA1(I)
300 FORMAT(13)
        C IA1(I)=NO. OF POINTS ON I-TH CONTOUR ,IA1(N+1)= NO. OF POINTS
        C ON PIEZ. SURFACE ,IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
        IA2=IA2+IA1(I)
300 FORMAT(13)
C IA1(I)=NO. OF POINTS ON I-TH CONTOUR ,IA1(N+1)= NO. OF POINTS
C ON PIEZ. SURFACE ,IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
C IA2=TOTAL NO. OF POINTS SPECIFIED
    IF(IA1(I)-IMAXA1)5,5,6
6 IMAXA1=IA1(I)
    5 CONTINUE
    IF(IA2-50)4,4,3
13 STOP
3 IF(IMAXA1-50)2,2,3
2 N1=N+1
    IL=IA1(I)
    DO 7 J=1,2
        READ(3,400)(A(I,J,K),K=1,IL)
400 FORMAT(2X,7F10.0)
        C READS ALL X VALUES FOR ONE CONTOUR (INCL. PIEZO. SURFACE) FOLLOWED
        C BY Y VALUES FOR THAT CONTOUR
        ILA=IA1(N2)
        READ(3,228)(A(N2,1,K),K=1,ILA)
228 FORMAT(2X,7F10.0)
C READS X VALUES FOR SURCHARGE LIMITS
    CALL SOLVE
    X1(1)=XMIN
    I=2
    J=2
206 IF(X(I)-X(I-1))209,207,209
207 I=I+1
209 IF(X(I)-(X(I-1)+AL))8,8,10
10 X1(J) = X1(J-1) + AL
   J = J + 1
   GO TO 209
8 X1(J) = X(I)
   IF(X1(J) - XMAX) 11, 12, 11
11 I = I + 1
   J = J + 1
   GO TO 206
C ENSURES MAX. DIFF. IN X1 = AL AND NO X1 VALUE IS DUPLIC.
12 I1 = J - 1
C II = TOTAL NO. OF SLICES IN FULL C.S.
WRITE(2, 501)
501 FORMAT(//)
WRITE(2, 500) I1
500 FORMAT(35H TOTAL NO OF SLICES IN FULL C.S. = , 13//)
14 CALL CALC
CALL RESULT
GO TO 417
13 STOP
END
SUBROUTINE SOLVE
COMMON/HOLD1/N2
COMMON/HOLD3/IA2, X
COMMON/HOLD5/N, A, IA1
COMMON/HOLD6/I1
DIMENSION IA1(7), X(50), A(7, 2, 50)
I1 = IA1(1)
DO 15 I = 1, I1
   15 X(I) = A(1, 1, I)
IPA = IL1 + 1
DO 16 I = IPA, 12
16 X(I) = 0.
C STORES VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
DO 18 I = 2, N2
   IL = IA1(I)
   DO 18 K = 2, IL
20 M = M + 1
   IF(A(I, 1, K) - X(M)) 19, 18, 20
19 J = IA2
22 X(J) = X(J - 1)
   J = J - 1
   IF(J - (M + 1)) 178, 22, 22
178 X(M) = A(I, 1, K)
18 CONTINUE
C INSERTS OTHER X COORD. IN APPROPRIATE POSITIONS
RETURN
END
SUBROUTINE CALC
COMMON/HOLD2/N1, X1
COMMON/HOLD3/IA2, X
COMMON/HOLD4/I1
COMMON/HOLD5/N, A, IA1
COMMON/HOLD7/DX, X2, Y, NM, S, W
DIMENSION IP(6), DX(200), X2(200), X1(200), Y(6, 200), W(5, 200),
IS(4, 4), SUR(4), A(7, 2, 50), IA1(7), X(50)
IF(IA1(N+2)-5)451,451,452
452 STOP
451 DO 23 I=1,11
   DX(I)=X1(I+1)-X1(I)
23 X2(I)=(X1(I)+X1(I+1))*0.5
C X2(I)=X COORD. AT MIDDLE OF SLICE (I)
   DO 24 J=1,NM
      IP(J)=1
      K=IP(J)
      DO 24 I=1,11
         IF(X2(I)-A(J,1,K+1))24,24,25
      24 K=K+1
      IF(A(J,1,K+1)-A(J,1,K))24,273.,24
      271 K=K-1
      Y(J,I)=A(J,2,K)+(A(J,2,K-1)-A(J,2,K))*(X2(I)-A(J,1,K))/
            1(A(J,1,K+1)-A(J,1,K))
C Y(J,I)=Y COORD. OF CONTOUR (J) AT MIDDLE OF SLICE (I)
   ILN=IA1(N+2)-1
   READ(3,226)(SUR(M),M=1, ILN)
226 FORMAT(2X,7F10.0)
C SUR(M)=SURCHARGE TO RIGHT OF POINT A(N+2,1,M)
   NM=1
   DO 26 J=1,NM
      600 FORMAT(2X,4F10.0)
   600 FORMAT(2X,4F10.0)
C S(J,K)=SOIL PROPERTY BELOW CONTOUR (J) AND TOP CONTOUR IS J=1,
C K=1 FOR DENSITY, K=2 FOR COHESION, K=3 FOR FRICTION (TAN), K=4 FOR RU
   M=1
   DO 27 I=1,11
      IF(X2(I)-A(N+2,1,M+1))591,591,592
      592 M=M+1
      591 W(1,I)=DX(I)*SUR(M)
      DO 27 J=1,NM
         W(J+1,I)=W(J,I)+DX(I)*(Y(J,I)-Y(J+1,I))*S(J,1)
C W(J,I)=WT OF SLICE (I) DOWN TO CONTOUR (J)
RETURN
END
SUBROUTINE RESULT
COMMON/HOLD4/I1
COMMON/HOLD5/N,A,IA1
COMMON/HOLD7/DX,X2,Y,NM,S,W
DIMENSION C(200),TERMA(200),TERMC(200),TERMD(200),F(40),X2(200),
1 DX(200),Y(6,200),W(5,200),S(4,4),A(7,2,50),AMAX(40),AX1(200),
2 AX2(200),XNET(200),TERMT(200),TERME(200),IA1(7),
3 WU(200),COM(200),FRI(200),COH(200),BIN(200),PIN(200),PIN1(200)
WRITE(2,222)
222 FORMAT(72H NO. 	 HT 	 XC 	 YC SLICES F(0) 	 F(M) 	 M F(K1
1) K1 COMMENT//)
   ZNC=0.
679 READ(3,508)HT
508 FORMAT(F10.0)
   IF(HT .LT. 0.)RETURN
   READ(3,3301)NX1,NX2,NDX,NY1,NY2,NDY
3301 FORMAT(6I5)
DO 37 MY=NY1, NY2, NDY
YC=MY
R=YC-HT
R2=R*R
DO 37 MX=NX1, NX2, NDX
XC=MX
ZNC=ZNC+1.
IFIRST=0
LAST=0
DO 39 I=1, N1
IF(ABS(XC-X2(I))-R)38, 38, 39
38 C(I)=YC-SQRT(R2-(XC-X2(I))*(XC-X2(I)))
IF(C(I)-Y(1, I))40, 42, 42
40 LAST=I
IF(IFIRST)42, 41, 42
41 IFIRST=I
42 IF(C(I)-Y(N, I))43, 42, 42
39 CONTINUE
C IFIRST(LAST)=NO. OF FIRST(LAST) SLICE WITHIN THE CIRCLE
IF(IFIRST)45, 44, 45
44 IF(LAST)45, 46, 45
45 IF(Y(1, IFIRST)-YC)47, 47, 48
46 IF(Y(1, LAST)-YC)49, 49, 48
47 ISLIC=LAST-IFIRST+1
C ISLIC=NO. OF SLICES WHOSE MID-ORDINATE IS CUT BY THE CIRCLE CONSIDERED
IF(ISLIC-3)50, 50, 51
51 IF(IFIRST-1)53, 54, 55
52 IF(LAST-1)55, 54, 55
C PROCEED WITH ANALYSIS OF THIS CIRCLE
55 CENTRE=(X2(LAST)+DX(LAST)/2.+X2(IFIRST)-DX(IFIRST)/2.)/2.
DO 602 I=IFIRST, LAST
IF(CENTRE-X2(I))603, 601, 602
602 CONTINUE
603 IF(ABS(CENTRE-X2(I))-(CENTRE_X2(I_1)))601, 601, 605
601 CENTRE=X2(I)
H=Y(I, I)-C(I)
GO TO 607
605 CENTRE=X2(I-1)
H=Y(I, I-1)-C(I-1)
607 FACTOR=5.
CONST1=X2(IFIRST)-DX(IFIRST)/2.
CONST2=X2(LAST)+DX(LAST)/2.
SUMA=0.
SUMB=0.
NUMBER=0
DO 60 I=IFIRST, LAST
IF(C(I)-Y(1, I))57, 56, 56
57 DIST1=X2(I)-DX(I)/2.-CONST1
IF(DIST1+CONST1-CENTRE)391, 391, 392
391 AXI(I)=DIST1/(CENTRE-CONST1)
GO TO 301
392 AXI(I)=(CONST2-(DIST1+CONST1))/(CONST2-CENTRE)
393 AX2(I)=DIST2/(CENTRE-CONST1)
GO TO 305
394 AX2(I)=(CONST2-(DIST2+CONST1))/(CONST2-CENTRE)
308  \text{XNET}(I) = \text{AX}1(I) - \text{AX}2(I)
\text{DO 58 } J=1,\text{NM}
\text{IP}(C(I)-Y(J+1, I))58,58,59
\text{58 CONTINUE}
59  \text{W}1=W(J, I)+(Y(J, I)-C(I))*DX(I)*S(J,1)
\text{TERM}(I)=(YC-C(I))/R
\text{TERMD}(I)=S(J,3)*(XC-X2(I))/R
\text{TERMT}(I)=(XC-X2(I))/(YC-C(I))
\text{TERMX}(I) = XNET(I)*S(J,3)
\text{TERME}(I) = W1*TERMT(I)
\text{COM}(I) = S(J,2)*DX(I)*TERMT(I)
\text{FRI}(I) = S(J,3)
\text{COH}(I) = S(J,3)*DX(I)/TERMC(I)
\text{IF}(S(J,4))82,81,81
81  \text{TERMA}(I) = S(J,2)*DX(I)+S(J,3)*W1*(1-S(J,4))
\text{WU}(I) = W1*(1-S(J,4))
\text{BIN}(I) = W1*(\text{TERMC}(I)-S(J,4)/\text{TERMC}(I))
\text{IF}(\text{BIN}(I) . GE. 0.) \text{GO TO 361}
\text{BIN}(I) = 0.
\text{NUMBER}=\text{NUMBER}+1
361  \text{SUMA}=\text{SUMA}+S(J,2)*DX(I)/\text{TERMC}(I)+S(J,3)*\text{BIN}(I)
\text{GO TO 60}
82  U=62.4*(Y(N+1, I)-C(I))
\text{IF}(U)83,84,84
83  U=0.
84  \text{TERMA}(I) = S(J,2)*DX(I)+S(J,3)*(W1-U*DX(I))
\text{WU}(I) = W1-U*DX(I)
\text{BIN}(I) = W1*\text{TERMC}(I)-U*DX(I)/\text{TERMC}(I)
\text{IF}(\text{BIN}(I) . GE. 0.) \text{GO TO 362}
\text{BIN}(I) = 0.
\text{NUMBER}=\text{NUMBER}+1
362  \text{SUMA}=\text{SUMA}+S(J,2)*DX(I)/\text{TERMC}(I)+S(J,3)*\text{BIN}(I)
\text{GO TO 60}
60  \text{SUMB}=\text{SUMB}+W1*(XC-X2(I))
\text{C SUMB IS +VE IF CENTROID TO L, OF CENTRE}
\text{WRITE}(2,7373)\text{NUMBER}
7373  \text{FORMAT}(9H \text{NUMBER=},13)
\text{SUMB}=\text{SUMB}/R
\text{IF}(\text{SUMB})86,85,85
86  \text{DO 87 } I=\text{IFIRST, LAST}
\text{TERM}(I) = -\text{TERMT}(I)
\text{TERME}(I) = -\text{TERME}(I)
\text{COM}(I) = -\text{COM}(I)
87  \text{TERMD}(I) = -\text{TERMD}(I)
\text{SUMB} = \text{SUMB}
\text{C CENTROID TO R, OF CENTRE}
85  \text{F}(0) = \text{SUMA}/\text{SUMB}
\text{C NEGLECTS FORCES BETWEEN SLICES}
\text{DO 89 } K1=1,20
\text{SUMC}=0.
\text{TOTAL}=0.
\text{DO 88 } I=\text{IFIRST, LAST}
\text{SA}=\text{WU}(I)-\text{COM}(I)/\text{F}(K1-1)
\text{SB}=\text{TERMC}(I)+\text{TERMD}(I)/\text{F}(K1-1)
\text{PIN}(I) = \text{SA}/\text{SB}
\text{IF}(\text{PIN}(I) . GE. 0.) \text{GO TO 88}
\text{PIN}(I) = 0.
\text{TOTAL} = \text{TOTAL} + 1.
C PIN= EFFECTIVE NORMAL FORCE AT BASE OF SLICE

SS SUMC= SUMC+COH(I)+PIN(I)*FRI(I)
WRITE(2,8130)K1,TOTAL

8130 FORMAT(5H K1= ,I3,8H TOTAL= ,F4.0)
F(K1)=SUMC/SUMB
IF(ABS(F(K1)-F(K1-1))<0.005)91,89,89
89 CONTINUE
WRITE(2,130)ZNC,HT,XC,YC,ISLIC,F(0),F(K1),K1

130 FORMAT(5H TOTAL= ,F4.0)
WRITE(2,801)BIN(I),I=IFIRST,LAST
WRITE(2,1801)PIN(I),I=IFIRST,LAST

1801 FORMAT(6H PIN ,5(F11.2,2X))
GO TO 37
91 F(M)=F(K1)
M=K1
919 AMAX(0)=FACTOR*H*H
L=0
908 L1=L+1
L2=L+20
DO 821 L=L1,L2
SUMNUM=0.
SUMDEN=0.
DO 411 I=IFIRST,LAST
D1=TERMC(I)*(TERMC(I)*F(K1)+TERMD(I))
SUMNUM=SUMNUM+(TERMA(I)+AMAX(L-1)*TERMX(I))/D1-TERME(I)-AMAX(L-1)*XNET(I)*TERWF(I)
411 SUMDEN=SUMDEN+TERMX(I)/D1-XNET(I)*TERMT(I)
MAX=L=AMAX(L-1)-SUMNUM/SUMDEN
IF(ABS(MAX-AMAX(L-1))<0.005)812,812,
821 CONTINUE
WRITE(2,170)ZNC,FIT,XC,YC,ISLIC,F(0),FM),M
170 FORMAT(5H TOTAL= ,F4.0)
WRITE(2,171)AMAX(0),AMAX(L),L,FACTOR
171 FORMAT(9H AMAX(0)=,F7.0,9H AMAX(L)=,F7.0,3H L=,13,8H FACTOR=,F4.0,
122H AMAX(0) NOT SUITABLE//)
FACTOR=FACTOR+.1.
GO TO 919
812 K2=K1+1
K3=K1+20
DO 902 K1=K2,K3
SUMC1=0.
TOTALX=0.
DO 903 I=IFIRST,LAST
SA1=WU(I)-COH(I)/F(K1-1)+XNET(I)*AMAX(L)
SB1=TERMC(I)+TERMD(I)/F(K1-1)
PIN1(I)=SA1/5131
IF(PIN1(I).GE.0.)GO TO 903
PIN1(I)=0.
TOTALX=TOTALX+1.
C PIN1= EFFECTIVE NORMAL FORCE AT BASE OF SLICE(ALLOWING FOR SIDE
C FORCES X AND E)

903 SUMC1=SUMC1+COH(I)+PIN1(I)*FRI(I)
WRITE(2,9210)K1,TOTALX
9210 FORMAT(5H K1= ,I3,9H TOTALX= ,F4.0)
F(K1)=SUMC1/SUMB
IF(ABS(F(K1)-F(K1-1))<0.005)904,902,902
902 CONTINUE
WRITE(2,9220)
9220 FORMAT(/)
GO TO 908
904 IF(K1 .EQ. K2)GO TO 3121
WRITE(2,9230)
9230 FORMAT(/)
GO TO 908
3121 WRITE(2,214)ZNC,HT,XC,YC,ISLIC,F(0),F(M),M,F(K1),K1
214 FORMAT(F5.0,1H ,3(F4.0,2X),13,3H ,F6.3,2H ,F6.3,2H ,I3,2H ,I3)
WRITE(2,702)SUMA,SUMB
702 FORMAT(7H SUMA= ,F13.2,7H SUMB= ,F13.2)
WRITE(2,802)(BIN(I),I=IFIRST,LAST)
802 FORMAT(6H BIN ,5(F11.2,2X))
WRITE(2,1802)(PIN(I),I=IFIRST,LAST)
1802 FORMAT(6H PIN ,5(F11.2,2X))
WRITE(2,1803)(PIN1(I) ,I=IFIRST,LAST)
1803 FORMAT(7H PIN1 ,5(F11.2,2X))
WRITE(2,196 )AMAX(n),AMAX(L),L,FACTOR
196 FORMAT(9H AMAX(0)=,F7.0,3H AMAX(L)=,F7.0,3H L=,I3,8H FACTOR=,F4.0/1/)
GO TO 37
C CONSIDER NEXT CIRCLE
43 WRITE(2,350)ZNC,HT,XC,YC
350 FORMAT(F5.0,1H ,3(F4.0,2X),67H)
1 CIRCLE CUTS BOTTOM CONTOUR/
GO TO 37
46 WRITE(2,450)ZNC,HT,XC,YC
450 FORMAT(F5.0,1H ,3(F4.0,2X),58H)
1 CIRCLE DOESNT CUT/
GO TO 37
48 WRITE(2,550)ZNC,HT,XC,YC
550 FORMAT(F5.0,1H ,3(F4.0,2X),75H)
1 TOP CONTOUR CUTS UPPER SEMI CIRCLE/
GO TO 37
50 WRITE(2,650)ZNC,HT,XC,YC,ISLIC
650 FORMAT(F5.0,1H ,3(F4.0,2X),I3,52H)
1 TOO FEW SLICES/
GO TO 37
52 C(I1+1)=YC-SQRT(R2-XC*XC)
IF(C(I1+1)-A(1,2,1))61,53, 53
61 WRITE(2,750)ZNC,HT,XC,YC,ISLIC
750 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H)
1 CIRCLE CUTS L.H. EDGE/
GO TO 37
54 C(I1+1)=YC-SQRT(R2-(X2(I1)-XC+DX(I1)*0.5)*(X2(I1)-XC+DX(I1)*0.5))
IF(C(I1+1)-A(1,2,11))62,55,55
62 WRITE(2,850)ZNC,HT,XC,YC,ISLIC
850 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H)
1 CIRCLE CUTS R.H. EDGE/
GO TO 37
56 WRITE(2,950)ZNC,HT,XC,YC,ISLIC
950 FORMAT(F5.0,1H ,3(F4.0,2X),I3,55H)
1 CIRCLE CUTS TWICE/
37 CONTINUE
GO TO 679
28 RETURN
END
&RUN;
APPENDIX VI

PROGRAM 14

FOR CALCULATING THE HORIZONTAL SIDE FORCES AND DETERMINING THE POSITION OF THE LINE OF THRUST

&JOB;STABILITY ANALYSIS OF SLOPE 14 (LINE OF THRUST)

&FORTRAN;

COMMON/HOLD1/N2
COMMON/HOLD2/N1,X1
COMMON/HOLD3/IA2,X,A,IA1
COMMON/HOLD4/I1
COMMON/HOLD5/N
DIMENSION IA1(7), X(50), X1(155), A(7,2,50)

3417 READ(3,3420)ICNTRL
3420 FORMAT(15)
817 READ(3,200)XMAX, AL, N
200 FORMAT(2F10.0, 13)
21 STOP
17 IA2=0
IMAXA1=0
N2=N+2
DO 5 I=1,N2
READ(3,300)IA1(I)
300 FORMAT (13)
C IA1(I)=NO. OF POINTS ON I-TH CONTOUR , IA1(N+1)= NO. OF POINTS ON PIEZO. SURFACE , IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
IA2=IA2+IA1(I)
C IA2=TOTAL NO. OF POINTS SPECIFIED
IF (IA1(I)-IMAXA1)5,5,6
6 IMAXA1=IA1(I)
5 CONTINUE
IF (IA2-50)4,4,3
3 STOP
4 IF (IMAXA1-50)2,2,3
2 N1=N-1
DO 7 I=1,N1
IL=IA1(I)
DO 7 J=1,2
7 READ(3,400)(A(I,J,K), K=1,IL)
400 FORMAT(2X,7F10.0)
C READS ALL X VALUES FOR ONE CONTOUR (INCL. PIEZO. SURFACE) FOLLOWED BY Y VALUES FOR THAT CONTOUR
ILA=IA1(N2)
READ(3,228)(A(N2,1,K),K=1,ILA)
228 FORMAT(2X,7F10.0)
C READS X VALUES FOR SURCHARGE LIMITS
CALL SOLVE
X1(1)=0.
I=2
J=2
206 IF (X(I)-X(I-1))209,207,209
207 I=I+1
209  IF(X(I)-(X1(J-1)+AL))8,8,10
10  X1(J)=X1(J-1)+AL
     J=J+1
     GO TO 209
8  X1(J)=X(I)
     IF(X1(J)-XMAX)11,12,11
11  I=I+1
     J=J+1
     GO TO 206
C ENSURES MAX. DIFF. IN X1 =AL AND NO X1 VALUE IS DUPLIC.
12  I1=J-1
C I1=TOTAL NO. OF SLICES IN FULL C.S.
WRITE(2,501)
501 FORMAT(//)
WRITE(2,500)I1
500 FORMAT(35H TOTAL NO OF SLICES IN FULL C.S. = ,13//)
IF(I1 .GT. 155)GO TO 13
14  CALL CALC
    CALL RESULT
    GO TO 3417
13  STOP
END
SUBROUTINE SOLVE
COMMON/HOLD1/N2
COMMON/EOLD3/1A2 , X, A, IA1
COMMON/HOLD5/N
DIMENSION IA1(7),X(50),A(7,2,
so)
IL1=IA1(1)
DO 15 I=1,IL1
15  X(I)=A(1,1,I)
IPA=IL1+1
DO 16 I=IPA,1A2
16  X(I)=0.
C STORES VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
DO 18 I=2,N2
18  M=1
    IL=IA1(I)
    DO 18 K=2,IL
20  M=M+1
    IF(A(I,1,K)-X(M))19, 18,20
19  J=IA2
22  X(J)=X(J-1)
     J=J-1
     IF(J-(M+1))178,22,22
178  X(M)=A(I,1,K)
20  CONTINUE
C INSERTS OTHER X COORD. IN APPROPRIATE POSITIONS
RETURN
END
SUBROUTINE CALC
COMMON/HOLD2/N1 ,X1
COMMON/HOLD3/IA2, X, A, IA1
COMMON/HOLD4/I1
COMMON/HOLD5/N
COMMON/HOLD7/DX,X2,Y,NM,W,S
DIMENSION IP(6),DX(155),X2(155),X1(155),Y(6,155),W(5,155),
209 IF(X(I)-(X1(J-1)+AL))8,8,10
10 X1(J)=X1(J-1)+AL
    J=J+1
    GO TO 209
8 X1(J)=X(I)
11 I=I+1
    J=J+1
    GO TO 206
C ENSURES MAX. DIFF. IN X1 =AL AND NO X1 VALUE IS DUPLIC.
12 II=J-1
C II=TOTAL NO. OF SLICES IN FULL C.S.
WRITE(2,501)
501 FORMAT(//)
WRITE(2,500)II
500 FORMAT(35H TOTAL NO OF SLICES IN FULL C.S. = ,13//)
IF(II .GT. 155)GO TO 13
14 CALL CALC
   CALL RESULT
   GO TO 3417
13 STOP
END
SUBROUTINE SOLVE
COMMON/HOLD1/N2
COMMON/HOLD3/IA2,X,A,IA1
COMMON/HOLD5/N
DIMENSION IA1(7),X(50),A(7,2,50)
IL1=IA1(1)
DO 15 I=1,IL1
   15 X(I)=A(1,1,I)
IPA=IL1+1
DO 16 I=IPA,1A2
   16 X(I)=0.
C STORES VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
DO 18 I=2,N2
   M=1
   IL=IA1(I)
   DO 18 K=2,IL
      20 M=M+1
      IF(A(I,1,K)-X(M))19,18,20
      19 J=IA2
         22 X(J)=X(J-1)
             J=J-1
             IF(J-(M+1))178,22,22
      18 CONTINUE
C INSERTS OTHER X COORD. IN APPROPRIATE POSITIONS
RETURN
END
SUBROUTINE CALC
COMMON/HOLD2/N1,X1
COMMON/HOLD3/IA2,X,A,IA1
COMMON/HOLD4/I1
COMMON/HOLD5/N
COMMON/HOLD7/DX,X2,Y,NM,W,S
DIMENSION IP(6),DX(155),X2(155),X1(155),Y(6,155),W(5,155),
\begin{verbatim}
1S(4,4),SUR(4),A(7,2,50),IA1(7),X(50)
IF(IA1(N+2)-5)451,451,452
452 STOP
451 DO 23 I=1,11
   DX(I)=X1(I+1)-X1(I)
23 X2(I)=(X1(I)+X1(I+1))*0.5

C X2(I)=X COORD. AT MIDDLE OF SLICE (I)
   DO 24 J=1,N,1
       IP(J)=1
       K=IP(J)
   DO 24 I=1,11
       IF(X2(I)-A(J,1,K+1))24,24,25
       K=K+1
       IF(A(J,1,K+1)-A(J,1,K))24,271,24
   271 K=K+1
   24 Y(J,I)=A(J,2,K)+*(A(J,2,K+1)-A(J,2,K))*(X2(I)-A(J,1,K))/
   1(A(J,1,K+1)-A(J,1,K))
C Y(J,I)=Y COORD. OF CONTOUR (J) AT MIDDLE OF SLICE (I)

ILN=IA1(N-I-2)-1
READ(3,226)(SUR(M),M=1,ILN)
226 FORMAT(2X,7F10.0)
C SUR(M)=SURCHARGE TO RIGHT OF POINT A(N+2,1,M)

NM=N-1
DO 26 J=1,NM
   26 READ(3,600)(S(J,K),K=1,4)
600 FORMAT(2X,4F10.0)
C S(J,K)=SOIL PROPERTY BELOW CONTOUR (J) AND TOP CONTOUR IS J=1,
C K=1 FOR DENSITY, K=2 FOR COHESION, K=3 FOR FRICTION (TAN), K=4 FOR RU
M=1
   DO 27 I=1,11
      IF(X2(I)-A(N-I-2,1,M+1))591,591,592
      592 M=M-1
   DO 27 J=1,NM
      27 W(J+1,I)=W(J,I)+DX(I)*(Y(J,I)-Y(J+1,I))*S(J,1)
C W(J,I)=WT. OF SLICE (I) DOWN TO CONTOUR (J)
RETURN
END
SUBROUTINE RESULT
COMMON/HOLD4/I1
COMMON/HOLD5/N
COMMON/HOLD7/DX,X2,Y,NM,W,S
DIMENSION C(155),TERMA(155),TERMC(155),TERMD(155),X2(155),DX(155),
1Y(6,155),W(5,155),S(4,4),AX1(155),AX2(155),XNET(155),TERMT(155),
2A1(155),TERMX(155),TERME(155),DI(155),WI(155),EI(155),E2(155),
3RATIO(155),A2(155),PN1(155),SN(155),PN2(155),SNE(155),HA(4,155),
4SMV(155)
READ(3,739)HT,XC,YC,AMAX,F2,ISLIC
739 FORMAT(4F10.0,F6.3,13)
R=YC-HT
R2=R*R
IPRIST=0
LAST=0
DO 39 I=1,11
   IF(ABS(XC-X2(I))-R)38,38,39
38 C(I)=YC-SQRT(R2-(XC-X2(I))*(XC-X2(I)))
\end{verbatim}
\[
\text{IF}(C(I)-Y(1,1)) = 40, 39, 39
\]
\[
\text{IIF}(\text{IFIRST}, \text{GT}, 0) \text{GO TO 39}
\]
\[
\text{IFIRST}=I
\]
\[
\text{CONTINUE}
\]
\[
\text{CIPRST(\text{LAST})=NO. OF FIRST(\text{LAST}) SLICE WITHIN THE CIRCLE}
\]
\[
\text{CIRCLE}=(X2(\text{LAST})+DX(\text{LAST})/2.+X2(\text{IFIRST})-DX(\text{IFIRST})/2.)/2.
\]
\[
\text{DO 602 I=IFIRST,LAST}
\]
\[
\text{IF(CENTRE-X2(I))}=603, 601, 602
\]
\[
\text{CONTINUE}
\]
\[
\text{IF(ABS(CENTRE-X2(I))-(CENTRE-X2(I-1)))=601, 601, 605}
\]
\[
\text{CENTRE}=X2(I)
\]
\[
\text{GO TO 607}
\]
\[
\text{CENTRE}=X2(I-1)
\]
\[
\text{CONST1}=X2(\text{IFIRST})-DX(\text{IFIRST})/2.
\]
\[
\text{CONST2}=X2(\text{LAST})-DX(\text{LAST})/2.
\]
\[
\text{SUMA}=0
\]
\[
\text{SUMB}=0
\]
\[
\text{DO 60 I=IFIRST,LAST}
\]
\[
\text{DIST1}=X2(I)-DX(I)/2.-\text{CONST1}
\]
\[
\text{IF(DIST1+\text{CONST1}-CENTRE)}=391, 391, 392
\]
\[
\text{AX1(I)}=\text{DIST1}/(\text{CENTRE}-\text{CONST1})
\]
\[
\text{GO TO 301}
\]
\[
\text{AX1(I)}=(\text{CONST2}-(\text{DIST1}+\text{CONST1}))/\text{(CONST2-CENTRE)}
\]
\[
\text{DIST2}=X2(I)+DX(I)/2.-\text{CONST1}
\]
\[
\text{IF(DIST2+\text{CONST1}-CENTRE)}=393, 393, 394
\]
\[
\text{AX2(I)}=\text{DIST2}/(\text{CENTRE}-\text{CONST1})
\]
\[
\text{GO TO 308}
\]
\[
\text{AX2(I)}=(\text{CONST2}-(\text{DIST2}+\text{CONST1}))/\text{(CONST2-CENTRE)}
\]
\[
\text{XNET(I)}=AX1(I)-AX2(I)
\]
\[
\text{DO 58 J=1, NM}
\]
\[
\text{IF(C(I)-Y(J+1, I))}=58, 58, 59
\]
\[
\text{CONTINUE}
\]
\[
\text{W1(I)}=W(J, I)+(Y(J, I)-C(I))*DX(I)*S(J,1)
\]
\[
\text{TERM(I)}=(\text{YC}-C(I))/R
\]
\[
\text{TERM(I)}=S(J,3)*(\text{YC}-X2(I))/R
\]
\[
\text{TERMT(I)}=(\text{XC}-X2(I))/(\text{YC}-C(I))
\]
\[
\text{TERMX(I)}=XNET(I)*S(J,3)
\]
\[
\text{TERME(I)}=\text{AX1(I)}*\text{TERMX(I)}
\]
\[
\text{IF(S(J,4))}=82, 83, 81
\]
\[
\text{TERMA(I)}=S(J,2)*DX(I)+S(J,3)*W1(I)*(1-S(J,4))
\]
\[
\text{SUMA}+S(J,2)*DX(I)/\text{TERM(C(I))}+S(J,3)*W1(I)*(\text{TERM(C(I))-S(J,4)}
\]
\[
\text{GO TO 60}
\]
\[
\text{U}=62.4*(\text{Y(N+1, I)}-C(I))
\]
\[
\text{IF(U)}=83, 84, 84
\]
\[
\text{U}=0
\]
\[
\text{TERMA(I)}=S(J,2)*DX(I)+S(J,3)*(W1(I)-U*DX(I))
\]
\[
\text{SUMA}+S(J,2)*DX(I)/\text{TERM(C(I))}+S(J,3)*(W1(I)*\text{TERM(C(I)}-U*DX(I))
\]
\[
\text{GO TO 60}
\]
\[
\text{SUMB}+W1(I)*(\text{XC}-X2(I))
\]
\[
\text{CSUM IS +VE IF CENTROID TO L. OF CENTRE(SLIP TO RIGHT)}
\]
\[
\text{CHECK}=1
\]
\[
\text{SUMB}=\text{SUMB}/R
\]
\[
\text{IF(SUMB)}=86, 85, 85
\]
\[
\text{CHECK}=-\text{CHECK}
\]
\[
\text{DO 87 I=IFIRST, LAST}
\]
TERMT(I) = -TERMT(I)
TERME(I) = -TERME(I)
87 TERM2(I) = -TERM2(I)
SUMS = -SUMB

C CENTROID TO R. OF CENTRE (SLIP TO LEFT)
85 F1 = SUMA/SUMB

C NEGLIFCTS FORCES BETWEEN SLICES
EI1(IFIRST) = 0.
SUME = 0.
DO 826 I = IFIRST, LAST
D1(I) = TERMC(I)*(TERM2(I)*F2 + TERM2(I))
ENET = (TERMA(I) + TERMX(I)*AMAX)/D1(I) - TERME(I) - (XNET(I)*AMAX*
1TERM2(I))
SUME = SUME + ENET

C E1(I), E2(I) ARE TOTAL HORIZONTAL FORCES ON LEFT AND RIGHT SIDE
C OF SLICE (I) RESP.
E2(I) = E1(I) - CHECK*ENET
E1(I+1) = E2(I)
SUMUV = 0.
SUMCV = 0.
DO 283 J = 1, NM
IF(C(I) .LT. Y(J+1, I)) GO TO 284
HA(J, I) = Y(J, I) - Y(J+1, I)
IF(S(J, 4) .LT. 0.0) GO TO 1191
UV = (S(J, 4)*W(J+1, I)*HA(J, I))/(2.*DX(I))
GO TO 1291
1191 U = 62.4*(Y(N+1, I) - Y(J+1, I))
IF(U) 1287, 1289, 1289
1287 U = 0.
1289 UV = U*HA(J, I)
1291 CV = S(J, 2)*HA(J, I)
SUMUV = SUMUV + UV
SUMCV = SUMCV + CV
283 CONTINUE
284 HA(J, I) = Y(J, I) - C(I)
IF(S(J, 4) .LT. 0.0) GO TO 1285
1285 PN1(I) = ((W1(I)*XNET(I)*AMAX)*TERM2(I) - ENET*TERM2(I)*TERM2(I)) -
1(S(J, 4)*W(I)*TERMC(I))
PN2(I) = PN1(I) * TERMC(I) / DX(I)
SN(1) = (S(J, 2)*DX(I)/TERMC(I) + S(J, 3)*PN1(I))/F2
SNE(I) = SN(1)*TERMC(I)/DX(I)
C PN1(I) = EFFECTIVE NORMAL FORCE ON BASE OF SLICE (I)
C PN2(I) = EFFECTIVE NORMAL STRESS ON BASE OF SLICE (I)
C SN(I) = MOBILISED SHEAR STRENGTH ON BASE OF SLICE (I)
C SNE(I) = MOBILISED SHEAR STRESS ON BASE OF SLICE (I)
C SMV(I) = MOBILISED SHEAR STRENGTH ALONG VERTICAL SIDE OF SLICE (I)
UV = S(J, 4)*HA(J, I)*HA(J, I)*S(J, 1)/2.
GO TO 828
285 U = 62.4*(Y(N+1, I) - C(I))
IF(U) 287, 289, 289
287 U = 0.
289 PN1(I) = ((W1(I)*XNET(I)*AMAX)*TERM2(I) - ENET*TERM2(I)*TERM2(I)) -
1(U*DX(I)/TERMC(I))
PN2(I) = PN1(I) * TERMC(I) / DX(I)
SN(1) = (S(J, 2)*DX(I)/TERMC(I) + S(J, 3)*PN1(I))/F2
SNE(I) = SN(1)*TERMC(I)/DX(I)
UV = U * HA(J, I) / 2

828 CV = S(J, 2) * HA(J, I)

SUMUV = SUMUV + UV

SUMCV = SUMCV + CV

SUMUV = STJMUV + UV

SUMCV = SUMCV + CV

SW(I) = (SUMCV + (E1(I) + E2(I)) / 2 - SIJMUV) / F2

IF(I .GT. IFIRST) GO TO 717

A1(I) = CHECK * DX(I) * TERMT(I) / 2.

GO TO 727

717 A1(I) = C(I) - A2(I - 1) - C(I)

727 A2(I) = (2 * E1(I) * A1(I) - (AX1(I) + AX2(I)) * AMAX * DX(I)) / (2 * E2(I))

Q = (A1(I) + A2(I)) / 2

HR = Y(I, I) - C(I)

C Q = DISTANCE FROM BASE OF SLICE TO LINE OF THRUST, HR = HEIGHT OF SLICE

826 RATIO(I) = Q / HR

C RATIO(I) = RATIO OF Q TO HR

WRITE(2, 569) F1

569 FORMAT(43H FACTOR OF SAFETY (NEGLECTING SIDE FORCES) =, F6.3)

WRITE(2, 964) IFIRST, LAST

964 FORMAT(9H FIRST = ,13, 8H LAST = ,13/)

WRITE(2, 939)(PN1(I), I = IFIRST, LAST)

939 FORMAT(6H PN1 ,7(F7.1,2X))

WRITE(2, 919)(PN2(I), I = IFIRST, LAST)

919 FORMAT(6H PN2 ,7(F7.1,2X))

WRITE(2, 803)(SN(I), I = IFIRST, LAST)

803 FORMAT(5H SN ,7(F7.1,2X))

WRITE(2, 1939)(SMV(I), T = IFIRST, LAST)

1939 FORMAT(61T SMV ,7(F7.1,2X))

WRITE(2, 829)(A1(I), I = IFIRST, LAST)

829 FORMAT(5H A1 ,7(F7.3,2X))

WRITE(2, 839)(A2(I), I = IFIRST, LAST)

839 FORMAT(5H A2 ,7(F7.3,2X))

WRITE(2, 864)(RATIO(I), I = IFIRST, LAST)

664 FORMAT(8H RATIO ,7(F7.3,2X))

WRITE(2, 764)(E1(I), I = IFIRST, LAST)

764 FORMAT(5H E1 ,7(F7.0,2X))

WRITE(2, 664)(E2(I), I = IFIRST, LAST)

664 FORMAT(5H E2 ,7(F7.0,2X))

WRITE(2, 772) SUME

772 FORMAT(8H SUME = ,F10.3//}}

RETURN

END

&RUN;
&JOB; STABILITY ANALYSIS OF SLOPE (SOLAR);
&FORTRAN;
COMMON/HOLD1/N2
COMMON/HOLD2/N1,X1,SUR
COMMON/HOLD3/IA2,X
COMMON/HOLD4/I1,S,NM
COMMON/HOLD5/N,A,IA1
COMMON/HOLD8/ICCHAR,XMAX
INTEGER ICHAR
DIMENSION IA1(7),X(50),X1(200),A(7,2,50),S(4,4),SUR(4),ICCHAR(68)
CALL SENTER
417 READ(3,1200)XMIN
1200 FORMAT(F10.0)
   IF(XMIN .EQ. -9999.)GO TO 13
   READ(3,200)XMAX,AL,N
200 FORMAT(2F10.0,13)
   IF(N-5)17, 17,21
21 STOP
17 IA2=0
   IMAXA1=0
   N2=N+2
   DO 5 I=1,N2
      READ(3,300)IA1(I)
300 FORMAT(13)
C IA1(I)=NO. OF POINTS ON I-TH CONTOUR ,IA1(N+1)= NO. OF POINTS
C ON PIEZ. SURFACE ,IA1(N+2)= NO. DEFINING SURCHARGE LIMITS
IA2=IA2+IA1(I)
C IA2=TOTAL NO. OF POINTS SPECIFIED
   IF(IA1(I)-IMAXA1)5, 5,6
5 IMAXA1=IA1(I)
   CONTINUE
   IF(IA2-50)4,4,3
3 STOP
4 IF(IMAXA1-50)2,2,3
2 N1=N+1
   DO 7 I=1,N1
      IL=IA1(I)
      DO 7 J=1,2
7 READ(3,400)(A(I,J,K),K=1,IL)
400 FORMAT(2X,7F10.0)
C READS ALL X VALUES FOR ONE CONTOUR (INCL. PIEZO. SURFACE) FOLLOWED
C BY Y VALUES FOR THAT CONTOUR AND REPEATS FOR OTHER CONTOURS
ILA=IA1(N2)
   READ(3,228)(A(N2,1,K),K=1,ILA)
228 FORMAT(2X,7F10.0)
C READS X VALUES FOR SURCHARGE LIMITS
ILN=IA1(N2)-1
   READ(3,226)(SUR(M),M=1,ILN)
226 FORMAT(2X,7F10.0)
C SUR(M)=SURCHARGE TO RIGHT OF POINT A(N2,1,M)
NM = N-1
DO 26 J = 1, NM
26 READ (3, 600) (S(J, K), K=1, 4)
600 FORMAT (2X, 7F10.0)
C S(J, K) = SOIL PROPERTY BELOW CONTOUR (J), TOP CONTOUR IS J = 1,
C K = 1 FOR DENSITY, K = 2 FOR COHESION, K = 3 FOR FRICTION (TAN), K = 4 FOR RU
ICHAR(1) = 35
ICHAR(2) = 47
ICHAR(3) = 46
ICHAR(4) = 52
ICHAR(5) = 50
ICHAR(6) = 62
ICHAR(7) = 20
ICHAR(8) = 56
ICHAR(9) = 57
ICHAR(10) = 62
ICHAR(11) = 20
ICHAR(12) = 48
ICHAR(13) = 47
ICHAR(14) = 41
ICHAR(15) = 46
ICHAR(16) = 52
ICHAR(17) = 62
ICHAR(18) = 20
ICHAR(19) = 35
ICHAR(20) = 40
ICHAR(21) = 33
ICHAR(22) = 46
ICHAR(23) = 39
ICHAR(24) = 37
ICHAR(25) = 62
ICHAR(26) = 20
ICHAR(27) = 51
ICHAR(28) = 47
ICHAR(29) = 41
ICHAR(30) = 44
ICHAR(31) = 62
ICHAR(32) = 20
ICHAR(33) = 48
ICHAR(34) = 50
ICHAR(35) = 48
ICHAR(36) = 62
ICHAR(37) = 20
ICHAR(38) = 52
ICHAR(39) = 45
ICHAR(40) = 37
ICHAR(41) = 62
ICHAR(42) = 20
ICHAR(43) = 56
ICHAR(44) = 35
ICHAR(45) = 62
ICHAR(46) = 20
ICHAR(47) = 57
ICHAR(48) = 35
ICHAR(49) = 62
ICHAR(50) = 20
DO 16 I=1A2,IA2
16 X(I)=0.
C STORES VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
   DO 18 I=2,N2
   M=1
   IL=IA1(I)
   DO 18 K=2,IL
20 M=M+1
   IF(A(I,1,K)-X(M))19,18,20
19 J=IA2
22 X(J)=X(J-1)
   J=J-1
   IF(J-(M+1))178,22,22
178 X(M)=A(I,1,K)
   CONTINUE
C INSERTS OTHER X COORD. IN APPROPRIATE POSITIONS
RETURN
END
SUBROUTINE CALC
COMMON/HOLD2/N1,X1,SUR
COMMON/HOLD3/IA2,X
COMMON/HOLD4/I1,S,NM
COMMON/HOLD5/N,A,IA1
COMMON/HOLD7/DX,X2,Y,W
DIMENSION IP(6),DX(200),X2(200),X1(200),Y,W
IS(4,4),SUR(4),A(7,2,50),IA1(7),X(50)
DO 23 I=1,11
 DX(I)=X1(I+1)-X1(I)
23 X2(I)=(X1(I)+X1(I+1))*0.5
C X2(I)=X COORD. AT MIDDLE OF SLICE (I)
   DO 24 J=1,N1
   IP(J)=1
   K=IP(J)
   DO 24 1=1,11
   IF(X2(I)-A(J,1,K+1))24,24,25
25 K=K+1
   IF(A(J,1,K+1)-A(J,1,K))24,271,24
271 K=K+1
24 Y(J,I)=A(J,2,K)+(A(J,2,K+1)-A(J,2,K))*X2(I)-A(J,1,K))/
1(A(J,1,K+1)-A(J,1,K))
C Y(J,I)=Y COORD. OF CONTOUR (J) AT MIDDLE OF SLICE (I)
   M=1
   DO 27 I=1,11
   IF(X2(I)-A(N+2,1,M+1))591,591,592
592 M=M+1
591 W(I,1)=DX(I)*SUR(M)
   DO 27 J=1,NM
27 W(J+1,1)=W(J,1)+DX(I)*(Y(J,I)-Y(J+1,I))*S(J,I)
C W(J,I)=W. OF SLICE (I) DOWN TO CONTOUR (J)
RETURN
END
SUBROUTINE RESULT
COMMON/HOLD4/I1,S,NM
COMMON/HOLD5/N,A,IA1
COMMON/HOLD6/I1
COMMON/HOLD7/DX,X2,Y,W
COMMON/HOLD8/ICARH,XMAX
INTEGER FILE
DIMENSION C(200),X2(200),Y(6,200),W(5,200),S(4,4),A(7,2,50),
1DX(200),ICHAR(68),TERMA(200),TERMC(200),TERM(200),TERM(200),
2TERMX(200),TERM(200),AX1(200),AX2(200),XNET(200),F(40),AMAX(40),
3FILE(1000),IA1(7)
WRITE(2,222)
222 FORMAT(2FH NO. HT XC YC SLICES F(0) F(M) M F(K1
1) K1 COMMENT//)
ZNC=0.
HT=20.
XC=50.
YC=80.
B=1020/XMAX
ISCALE=B
SCALE=ISCALE
5011 IHT=HT*SCALE
IXC=XC*SCALE
IYC=YC*SCALE
CALL DEFPIC(FILE,1000)
CALL MOVETO(1000,0.,FALSE.,0,7)
CALL LINE(-1000,0.,TRUE.)
CALL LINE(0,1000.,TRUE.)
CALL MOVETO(0,IHT.,FALSE.,0,7)
CALL LINE(1000.,0.,TRUE.)
I=1
617 MX1=A(I,1,1)*SCALE
MY1=A(I,2,1)*SCALE
CALL MOVETO(MX1,MY1.,FALSE.,0,7)
IL=IA1(I)
DO 381 K=2,IL
DO 381 J =1,2
IF(J .GT. 1) GO TO 34
MX=A(I,J,K)*SCALE
GO TO 381
34 MY=A(I,J,K)*SCALE
CALL LINE(MX-MX1,MY-MY1.,TRUE.)
MX1=MX
MY1=MY
381 CONTINUE
I=I+1
IF(I .LE. N) GO TO 617
R=YC-HT
XLIM=(XMAX+R-XC)*SCALE
R2=R*R
IR=R*SCALE
ZNC=ZNC+1.
ANGLE=3.141593/60.
IXB=0
IYB=0
SANGLE=0.
IXA1=IXC-IR
IYA1=IYC
IF(IXA1 .GE. 0) GO TO 231
IXA1=0
YL=SQRT(R2-XC*XC)
IYA1=(YC-YL)*SCALE
IXB=IR-IXC
IYB=1YC-IYAI
SANGLE=ATAN(YL/XC)

231 CALL MOVETO(IXA1, IYA1, 'FALSE.', 0, 7)
DO 113 I=1,66
XOLD=IXB
YOLD=IYB
SANGLE=SANGLE+ANG1E
XNEW=R*(1-COS(SANGLE))*SCALE
YNEW=R*SIN(SANGLE)*SCALE
IXA=XNEW-XOLD
IYA=YNEW-YOLD
IXB=IXB+IXA
IYB=IYB+IYAI
IF(XNEW-XLIM)<113, 113, 811
113 CALL LINE(IXA, -IYA, 'TRUE.')
811 CALL XHIBIT(FILE, 1000)
NDUM=1DUMP(NAME)
GO TO 509
5012 CONTR=().
XY=0.
POINT=0.
333 CALL SENDCH(ICHAR(1))
CALL RCHNGE CONTR)
ICONTR=CONTR
CALL SENDCH(ICHAR(8))
CALL RCHNGE(XY)
IXY=XY
CALL SENDCH ICHAR(12))
CALL RCHNGE(POINT)
IPOINT=POINT
CALL RCHNGE(A(ICONTR,IXY,IPOINT))
CHANGE=0.
CALL SENDCH ICHAR(19))
CALL RCHNGE(CHANGE)
IF(CHANGE .GT. 0)GO TO 333
711 SOIL=().
PRP=().
712 CALL SENDCH(ICHAR(27))
CALL RCHNGE(SOIL)
IF(SOIL .EQ. 0)GO TO 28
ISOIL=SOIL
CALL SENDCH(ICHAR(33))
CALL RCHNGE(PRP)
IPROP=PRP
CALL RCHNGE(S/ISOIL,IPROP))
TME=0.
CALL SENDCH(ICHAR(38))
CALL RCHNGE(TME)
IF(TME .GT. 0)GO TO 712
GO TO 28
509 IFIRST=0
LAST=0
DO 39 I=1,11
IF(ABS(XC-X2(I))-R)38,38,39
38  \text{C(I)} = \text{YC} - \sqrt{R^2 - (\text{XC} - \text{X2(I)})^2(\text{XC} - \text{X2(I)})^2}

\text{IF(C(I)} - \text{Y(1, I)}) 40, 42, 42

40 \text{LAST} = \text{I}

\text{IF(IFIRST)} 42, 41, 42

41 \text{IFIRST} = \text{I}

42 \text{IF(C(I)} - \text{Y(N, I)}) 43, 39, 39

39 \text{CONTINUE}

\text{C IFIRST(LAST)} = \text{NO}. \text{OF FIRST(LAST) SLICE WITHIN THE CIRCLE}

\text{IF(IFIRST)} 45, 44, 45

44 \text{IF(LAST)} 45, 46, 45

45 \text{IF(Y(1, IFIRST)} - \text{YC}) 47, 47, 48

47 \text{IF(Y(1, LAST)} - \text{YC}) 49, 49, 48

49 \text{ISLIC} = \text{LAST - IFIRST + 1}

\text{C ISLIC} = \text{NO}. \text{OF SLICES WHOSE MID-ORDINATE IS CUT BY THE CIRCLE CONSIDERED}

\text{IF(ISLIC)} 50, 50, 51

51 \text{IF(IFIRST - 1)} 53, 52, 53

53 \text{IF(LAST - I1)} 55, 54, 55

\text{C PROCEED WITH ANALYSIS OF THIS CIRCLE}

55 \text{CENTRE} = (\text{X2(LAST)} + \text{DX(LAST)} / 2. + \text{X2(IFIRST)} - \text{DX(IFIRST)} / 2.) / 2.

\text{DO 602 I = IFIRST, LAST}

\text{IF(CENTRE - X2(I))} 603, 601, 602

602 \text{CONTINUE}

603 \text{IF(ABS(CENTRE - X2(I)) - (CENTRE - X2(I - 1))} 601, 601, 605

601 \text{CENTRE} = \text{X2(I)}

\text{H} = \text{Y(1, I)} - \text{C(I)}

\text{GO TO 607}

605 \text{CENTRE} = \text{X2(I - 1)}

\text{H} = \text{Y(1, I - 1)} - \text{C(I - 1)}

607 \text{FACTOR} = -7.0

\text{CONST1} = \text{X2(IFIRST)} - \text{DX(IFIRST)} / 2.

\text{SUMA} = 0.

\text{SUMB} = 0.

\text{DO 60 I = IFIRST, LAST}

\text{IF(C(I)} - \text{Y(1, I)}) 57, 56, 56

57 \text{DIST1} = \text{X2(I)} - \text{DX(I)} / 2. - \text{CONST1}

\text{IF(DIST1 + CONST1 - CENTRE)} 391, 391, 392

391 \text{AX1(I)} = \text{DIST1} / (\text{CENTRE} - \text{CONST1})

\text{GO TO 301}

392 \text{AX1(I)} = (\text{CONST2} - (\text{DIST1} + \text{CONST1})) / (\text{CONST2} - \text{CENTRE})

301 \text{DIST2} = \text{X2(I)} + \text{DX(I)} / 2. - \text{CONST1}

\text{IF(DIST2 + CONST1 - CENTRE)} 393, 393, 394

393 \text{AX2(I)} = \text{DIST2} / (\text{CENTRE} - \text{CONST1})

\text{GO TO 308}

394 \text{AX2(I)} = (\text{CONST2} - (\text{DIST2} + \text{CONST1})) / (\text{CONST2} - \text{CENTRE})

308 \text{XNET(I)} = \text{AX1(I)} - \text{AX2(I)}

\text{DO 58 J = 1, NM}

\text{IF(C(I)} - \text{Y(J + 1, I)}) 58, 58, 59

58 \text{CONTINUE}

59 \text{W1} = \text{W(J, I)} + (\text{Y(J, I)} - \text{C(I)}) * \text{DX(I)} * \text{S(J, 1)}

\text{TERMC(I)} = (\text{YC - C(I)}) / \text{R}

\text{TERMD(I)} = \text{S(J, 3)} * (\text{XC} - \text{X2(I)}) / \text{R}

\text{TERMT(I)} = (\text{XC} - \text{X2(I)}) / (\text{YC - C(I)})

\text{TERMX(I)} = \text{XNET(I)} * \text{S(J, 3)}

\text{TERME(I)} = \text{W1} * \text{TERMT(I)}

\text{IF S(J, 4)} 82, 81, 81
81 \( T E R M A ( I ) = S ( J, 2 ) \times D X ( I ) + S ( J, 3 ) \times W 1 \times ( 1 - S ( J, 4 ) ) \)
\( SUM = SUM + S ( J, 2 ) \times DX ( I ) / T E R M C ( I ) + S ( J, 3 ) \times W 1 \times ( T E R M C ( I ) - S ( J, 4 ) ) / T E R M C ( I ) \)
GO TO 60

82 \( U = 6 2 . 5 \times ( Y ( N + 1 , I ) - C ( I ) ) \)
IF \( U \geq 0 . \) GO TO 84

84 \( T E R M A ( I ) = S ( J, 2 ) \times D X ( I ) + S ( J, 3 ) \times ( W 1 - U \times D X ( I ) ) \)
\( SUM = SUM + S ( J, 2 ) \times DX ( I ) / T E R M C ( I ) + S ( J, 3 ) \times ( W 1 \times T E R M C ( I ) - U \times D X ( I ) / T E R M C ( I ) ) \)

60 \( S U M B = S U M B + W 1 \times ( X C - X 2 ( I ) ) \)

C SUMB IS +VE IF CENTROID TO L. OF CENTRE
\( SUM = SUM / R \)
IF \( S U M B 
eq 6 5 , 8 5 , 8 5 \)

86 DO 87 \( I = I F I R S T , L A S T \)
\( T E R M T ( I ) = - T E R M T ( I ) \)
\( T E R M E ( I ) = - T E R M E ( I ) \)

87 \( T E R M D ( I ) = - T E R M D ( I ) \)
\( S U M B = - S U M B \)
C CENTROID TO R. OF CENTRE

85 \( F ( 0 ) = S U M A / S U M B \)
C NEGLECTS FORCES BETWEEN SLICES
DO 89 \( K 1 = 1 2 0 \)
\( S U M C = 0 . \)
\( S U M D = 0 . \)
DO 88 \( I = I F I R S T , L A S T \)
\( D = T E R M C ( I ) \times F ( K 1 - 1 ) + T E R M D ( I ) \)
\( S U M C = S U M C + T E R M A ( I ) / D \)

88 \( S U M D = S U M D + T E R M A ( I ) \times T E R M D ( I ) / ( D \times D ) \)
\( F ( K 1 ) = F ( K 1 - 1 ) \times ( 1 - ( S U M B - S U M C ) / ( S U M B - S U M D ) ) \)
IF \( A B S ( F ( K 1 ) - F ( K 1 - 1 ) ) = 0 . 0 0 5 \) 91, 89, 89

39 CONTINUE
WRITE(2,130)ZNC,HT,XC,YC,ISLIC,F(0),F(K1),K1

130 FORMAT(4(F4.0,2X),13,3H 	 ,F6.3,2H ,F6.3,2H ,I3,40H
1 ITERATION UNSATISFACTORY/)      
GO TO 37

91 \( F ( M ) = F ( K 1 ) \)
\( M = K 1 \)
919 \( A M A X ( 0 ) = F A C T O R \times H \times H \)
\( L = 0 \)
908 \( L 1 = L + 1 \)
\( L 2 = L + 2 0 \)
DO 821 \( L = L 1 , L 2 \)
\( S U M U N * = 0 . \)
\( S U M D E N * = 0 . \)
DO 411 \( I = I F I R S T , L A S T \)
\( D 1 = T E R M C ( I ) \times ( T E R M C ( I ) \times F ( K 1 ) + T E R M D ( I ) ) \)
\( S U M U N * = S U M U N * + ( T E R M A ( I ) + A M A X ( L - 1 ) \times T E R M X ( I ) ) / D 1 - T E R M E ( I ) - A M A X ( L - 1 ) \times T E R M T ( I ) \)
\( I = X N E T ( I ) \times T E R M T ( I ) \)

411 \( S U M D E N = S U M D E N + T E R M X ( I ) / D 1 - X N E T ( I ) \times T E R M T ( I ) \)
\( A M A X ( L ) = A M A X ( L - 1 ) - S U M U N * / S U M D E N \)
IF \( A B S ( A M A X ( L ) - A M A X ( L - 1 ) ) = 0 . 0 0 5 \) 512, 821, 821

821 CONTINUE
WRITE(2,171)AMAX(0),AMAX(L),L,FACTOR
170 FORMAT(4(F4.0,2X),13,3H 	 ,F6.3,2H ,F6.3,2H ,I3)
WRITE(2,171)AMAX(0),AMAX(L),L,FACTOR
FACTOR = FACTOR + 1.
GO TO 919.

812 K2 = K1 + 1
K3 = K1 + 20
DO 92 K1 = K2, K3
SUMC1 = 0.
SUMD1 = 0.
DO 903 I = IFIRST, LAST
G1 = TERRMA(I) + AMAX(L) * TERRX(I)
D2 = TERRC(I) * F(K1 - 1) + TERRD(I)
SUM1 = SUMC1 + G1 / D2
903 SUMD1 = SUMD1 + G1 * D2
F(K1) = F(K1 - 1) * (1 - SUMD1 / SUMD1) - 0.005
IF(ABS(F(K1)) < 0.005) GO TO 904, 912, 902

902 CONTINUE
GO TO 908.

904 IF(K1 .GT. K2) GO TO 908.
WRITE(2, 214) ZNC, NT, XC, YC, ISLIC, F(0), F(M), M, F(K1), K1
13)
WRITE(2, 196) AMAX(0), AMAX(L), L, FACTOR
196 FORMAT(9H AMAX(0)=, F7.0, 9H AMAX(L)=, F7.0, 3H L=, I3, 8H FACTOR=, F4.0/
1)
FK = F(K1)
CALL SENDCH(ICHAR(65))
CALL RCHNGE(FK)
WRITE(2, 350) ZNC, HT, XC, YC
350 FORMAT(4(F4.0, 2X), 6TH
1LE Cuts Bottom Contour/)
ERROR = 1.
CALL SENDCH(ICHAR(58))
CALL RCHNGE(ERROR)
IF(ERROR = 200.) 37, 444, 5012
WRITE(2, 43) ZNC, HT, XC, YC
43 FORMAT(4(F4.0, 2X), 67H
CIRC
1LE Cuts Bottom Contour/)
ERROR = 1.
CALL SENDCH(ICHAR(58))
CALL RCHNGE(ERROR)
IF(ERROR = 200.) 37, 444, 5012
WRITE(2, 46) ZNC, HT, XC, YC
46 FORMAT(4(F4.0, 2X), 58H
CIRC
1LE Doesnt Cut/)
ERROR = 2.
CALL SENDCH(ICHAR(58))
CALL RCHNGE(ERROR)
IF(ERROR = 200.) 37, 444, 5012
WRITE(2, 48) ZNC, HT, XC, YC
48 FORMAT(4(F4.0, 2X), 75H
TOP
1Contour Cuts Upper Semi Circle/)
ERROR = 3.
CALL SENDCH(ICHAR(58))
CALL RCHNGE(ERROR)
IF(ERROR = 200.) 37, 444, 5012
WRITE(2, 50) ZNC, HT, XC, YC
50 FORMAT(4(F4.0, 2X), 13, 52H
TOO
1Few Slices/)
ERROR = 4.
CALL SENDCH(ICHAR(58))
CALL RCHNGE(ERROR)
IF(ERROR = 200.)37,444,5012

52 C(I1+1)=YC-SQRT(R2-XC*XC)
   IF(C(I1+1)-A(I1,2,1))61,53,53

61 WRITE(2,750)ZNC,HT,XC,YC,ISLIC
750 FORMAT(4(F4.0,2X),13,59H CIRC
   ILE CUTS L.H. EDGE/)
   ERROR=5.
   CALL SENDCH(ICHAR(58))
   CALL RCHNGE(ERROR)
   IF(ERROR = 200.)37,444,5012

54 C(I1+1)=YC-SQRT(R2-(X2(I1)-XC+DX(I1)*0.5)*(X2(I1)-XC+DX(I1)*0.5))
   IF(C(I1+1)-A(I1,2,I1))62,55,55

62 WRITE(2,850)ZNC,HT,XC,YC,ISLIC
850 FORMAT(4(F4.O,2X),13,59H CIRC
   ILE CUTS R.H. EDGE/)
   ERROR=6.
   CALL SENDCH(ICHAR(58))
   CALL RCHNGE(ERROR)
   IF(ERROR = 200.)37,444,5012

56 WRITE(2,950)ZNC,HT,XC,YC,ISLIC
950 FORMAT(4(F4.0,2X),13,59H CIRC
   ILE CUTS TWICE/)
   ERROR=7.
   CALL SENDCH(ICHAR(58))
   CALL RCHNGE(ERROR)
   IF(ERROR = 200.)37,444,5012

444 CALL SENDCH(ICHAR(51))
   CALL RCHNGE(HT)

37 CALL SENDCH(ICHAR(43))
   CALL RCHNGE(XC)
   CALL SENDCH(ICHAR(47))
   CALL RCHNGE(YC)
   GO TO 5011

28 RETURN
END
&RUN;
PROGRAM 707

(SPINDLE SYSTEM)

&JOB;STABILITY ANALYSIS OF SLOPE 707(SPINDLE);
&FORTRAN;
COMM/HOLD1/A,N
COMMON/HOLD2/X,IA2
COMMON/HOLD3/I1,NM,S
COMMON/HOLD4/X1
COMMON/HOLD7/IA1
COMMON/HOLD8/HT,XMAX
DIMENSION IA1(5),X(50),X1(200),A(5,2,50),S(4,4)
CALL SETA
READ(3,763)XMIN
763 FORMAT(F10,0)
IF(XMIN .EQ. -9999)GO TO 13
READ(3,200)XMAX,AL,N
200 FORMAT(2F10.0,13)
IF(N-5)17,17,21
17 IA2=0
IMAXA1=0
DO 5 I=1,N
READ(3,300)IA1(I)
300 FORMAT(13)
C IA1(I)=NO. OF POINTS ON I-TH CONTOUR
IA2=IA2+IA1(I)
C IA2=TOTAL NO. OF POINTS SPECIFIED
IF(IA1(I)-IMAXA1)5,5,6
6 IMAXA1=IA1(I)
5 CONTINUE
IF(IA2-50)4,4,3
3 STOP
4 IF(IMAXA1-50)2,2,3
2 DO 7 I=1,N
IL=IA1(I)
DO 7 J=1,2
7 READ(3,400)(A(I,J,K),K=1,4)
C READ ALL X-COORD. FOR FIRST CONTOUR THEN Y-COORD. OF THAT CONTOUR
C AND REPEAT FOR OTHER CONTOURS
400 FORMAT(2X,7F10.0)
C READ ALL X-COORD. OF TOP CONTOUR FOLLOWED BY Y-COORD. OF THAT CONTOUR
NM=N-1
DO 26 J=1,NM
26 READ 3,600)(S(J,K),K=1,4)
600 FORMAT(2X,4F10.0)
C S(J,K)=SOIL PROPERTY IN ZONE IMMEDIATELY BELOW CONTOUR (J), TOP
C CONTOUR IS J=1, K=1 FOR DENSITY, K=2 FOR COHESION, K=3 FOR
C FRICTION(TAN), K=4 FOR RU
910 CALL SOLVE
X1(1)=XMIN
I=2
J=2
9 IF(X(I)-(X1(J-1)+AL))8,8,10
10 X1(J)=X1(J-1)+AL
   J=J+1
   GO TO 9
C ENSURE MAX. DIFF. IN X1 =AL
8 X1(J)=X(I)
   IF(X1(J)-XMAX)11,11,11
11 I=I+1
   J=J+1
   GO TO 9
12 I1=J-1
C I1=TOTAL NO. OF SLICES IN FULL C.S.
   WRITE(2,500)I1
500 FORMAT(34H TOTAL NO OF SLICES IN FULL C.S. = ,I3//)
IF(I1=200)14,13,13
14 CALL CALC
   CALL RESULT
   GO TO 910
13 STOP
END

SUBROUTINE SOLVE
COMMON/HOLD1/A,N
COMMON/HOLD2/X,IA2
COMMON/HOLD5/I11
COMMON/HOLD7/IA1
DIMENSION X(50),IA1(5),A(5,2,50)
I1=IA1(1)
   DO 15 I=1,I11
15 X(I)=A(1,1,I)
   IPA=IL1+1
   DO 16 I=IPA,IA2
16 X(I)=O.
C STORE VALUES OF X FOR TOP CONTOUR (IN ASCENDING ORDER)
   DO 18 I=2,N
      M=1
      IL=IA1(I)
      DO 18 K=2,IL
18 M=M+1
      IF(A(I,1,K)-X(M))19,18,20
19 J=IA2
22 X(J)=X(J-1)
   J=J-1
   IF(J-(N+1))178,22,22
178 X(M)=A(I,1,K)
20 CONTINUE
C ENSURE OTHER X-COORD. IN APPROPRIATE POSITIONS
RETURN
END

SUBROUTINE CALC
COMMON/HOLD1/A,N
COMMON/HOLD3/I1,NM,S
COMMON/HOLD4/X1
COMMON/HOLD6/DX,X2,Y,W
DIMENSION IP(5),DX(200),X2(200),Y(5,200),W(5,200),S(4,4),X1(200),IA(5,2,50)
DO 23 I=1,II
   DX(I)=X(I+1)-X(I)
23 X2(I)=(X(I)+X(I+1))/2
C X2(I)=X-COORD. AT MIDDLE OF SLICE(I)
   DO 24 J=1,N
      IP(J)=1
      K=IP(J)
   DO 24 I=1,II
      IF(X2(I)=A(J,1,(K+1)))24,24,25
25 K=K+1
24 Y(J,I)=A(J,2,K)+A(J,2,K+1)-A(J,2,K)*X2(I)-A(J,1,K))/
   (A(J,1,K+1)-A(J,1,K))
   DO 27 I=1,II
      W(I,1)=0.
   DO 27 J=1,NM
      W(J,I)=W(J,I)+DX(I)*(Y(J,I)-Y(J+1,I))*S(J,1)
   C W(J,1)==WT. OF SLICE (I) DOWN TO CONTOUR (J)
RETURN
END
SUBROUTINE RESULT
COMMON/HOLD1/A,N
COMMON/HOLD5/I1,NM,S
COMMON/HOLD6/DX,X2,Y,W
COMMON/HOLD7/HT,XMAX
INTEGER FILE
DIMENSION C(200),X2(200),Y(5,200),W(5,200),S(4,4),A(5,2,50),
   DX(200),TERMA(200),TERMC(200),TERMD 200),TERMT(200),
   TERMX(200),TERMEX(200),AX1(200),AX2(200),XNET(200),F 40),AMAX(40),
   FILE(1000),IA(5),IRAY(4)
WRITE (2,222)
222 FORMAT(72H NO. NT 	 XC 	 YC SLICES F 0) F(M) M F(K1
   1) K1 COMMENT//)
ZNC=0.
HT=20.
XC=50.
YC=80.
B=1020./XMAX
ISCALE=B
SCALE=ISCALE
CALL ENABLE(1)
CALL DISABLE(2)
MOVING=0
IHT=HT*SCALE
IXC=XC*SCALE
IYC=YC*SCALE
CALL TRSET (IXC, IYC)
CALL DEFPIC(FILE,1000)
CALL DEFSUB(LPOINT)
CALL LINE(5,5,.TRUE.)
CALL LINE(0,-10,.FALSE.)
CALL LINE(-10,10,.TRUE.)
CALL LINE(0,-10,.FALSE.)
CALL LINE(5,5,.TRUE.)
CALL ENDSUB(LPOINT)
CALL MOVETO(1000,0,FALSE.,0,7)
CALL LINE(-1000,0,TRUE.)
CALL LINE(0,1000,TRUE.)
CALL MOVETO(0,IHT,FALSE.,0,7)
CALL LINE(1000,0,TRUE.)
I=1

617 MX1=A(I,1,1)*SCALE
MY1=A(1,2,1)*SCALE
IGNORE=INSTAT(MX1,MY1,LPOINT,100*I+1)
CALL MSSLP(IGNORE)
IGNORE=NEWSEG(-1)
Il=IA1(I)
DO 381 K=2,IL
DO 381 J=1,2
IF(J.GT.1)GO TO 34
MX=A(I,J,K)*SCALE
GO TO 381
34 MY=A(I,J,K)*SCALE
CALL MOVETO(MX1,MY1,FALSE.,0,7)
CALL LINE(MX-MX1,MY-MY1,TRUE.)
IGNORE=INSTAT(MX,MY,LPOINT,100*I+K)
CALL MSSLP(IGNORE)
IGNORE=NEWSEG(-1)
MX1=MX
MY1=MY
381 CONTINUE
I=I+1
IF(I.LE.N)GO TO 617
R=YC-IHT
XLIM=(XMAX+R-XC)*SCALE
R2=R*R
IR=R*SCALE
ZNC=ZNC+1.
ANGLE=3.141593/60.
IXB=0
IYB=0
SANGLE=0.
IXA1=IXC-IR
IYAI=IYC
IF(IYA1.GE.0)GO TO 231
IXA1=0
YL=SQR(R2-XC*XC)
IYA1=(YC-YL)*SCALE
IXB=IR-IXC
IYB=IYC-IYA1
SANGLE=ATAN(YL/XC)
231 CALL MOVETO(Ixa1,lya1,FALSE.,0,7)
DO 113 1=1,60
XOLD=IXB
YOLD=IYB
SANGLE=SANGLE+ANGLE
XNEW=R*(1-COS(SANGLE))**SCALE
YNEW=R*SIN(SANGLE)**SCALE
IXA=XNEW-XOLD
IYA=YNEW-YOLD
IXB=IXB+IXA
IYB=IYB+IYA
IF XNEW-XLIM)113,113,811
113 CALL LINE(IXA,-IYA,.TRUE.)
811 CALL XHIBIT(FILE,1000)
IF(MOVING)509,444,446
444 CALL TRACK(IX, IY, ISTOP)
   IF(ISTOP .LT. 0)GO TO 444
   CALL ACTION(IRAY)
445 IF(IRAY(2) .EQ. 47)GO TO 6011
   IF(IRAY(2) .EQ. 52)GO TO 701
   IF(IRAY(2) .NE. 34)GO TO 444
448 CALL ENABLE(2)
   CALL ACTION(IRAY)
   CALL DISABLE(2)
   IF(IRAY(1) .EQ. 1)GO TO 445
   IGNORE=IRAY(2)
   IGNORE=FILE IGNORE)
   ICONTR=IGNORE/100
   IPOINT=MOD(IGNORE,100)
   IXSAVE=A(ICONTR,1, IPOINT)
   IYSAVE=A(ICONTR,2, IPOINT)
   CALL TRSET(IXSAVE*ISCALE, IYSAVE*ISCALE)
   MOVING=1
   GO TO 901
446 CALL TRACK(IX, IY, ISTOP)
   IF(ISTOP .GT. 0)GO TO 447
   A(ICONTR,1, IPOINT)=IX/ISCALE
   A(ICONTR,2, IPOINT)=IY/ISCALE
   GO TO 901
447 CALL ACTION(IRAY)
   IF(IRAY(2) .EQ. 38)RETURN
   IF(IRAY(2) .EQ. 45)GO TO 449
   IF(IRAY(2) .NE. 56)GO TO 446
   MOVING=0
   A(ICONTR,1, IPOINT)=IXSAVE
   A(ICONTR,2, IPOINT)=IYSAVE
   GO TO 901
449 CALL TRSET(IXC, IYC)
   GO TO 448
6011 IXC=IX
   IYC=IY
   XC=IXC/ISCALE
   YC=IYC/ISCALE
   MOVING=-1
   GO TO 901
701 IHT=IY
   HT=IHT/ISCALE
   CALL TRSET(IXC, IYC)
   GO TO 901
509 IFIRST=0
   LAST=0
   DO 39 I=1,I1
   IF(ABS(XC-X2(I))-R)>38,38,39
38 C(I)=YC-SQRT(R2-(XC-X2(I))2)*(XC-X2(I)))
   IF(C(I)>Y(I,1),40,42,42
40 LAST=I
   IF(IFIRST)>42,44,44
   IFIRST=I
   IF(C(I)>N(I),43,39,39
39 CONTINUE
C IFIRST-LAST)=NO. OF FIRST-LAST) SLICE WITHIN THE CIRCLE
   IF(IFIRST>45,44,45
   IF(LAST>45,46,45
   IF(Y(I,IFIRST)-YC)<47,47,47
   IF(Y(I,LAST)-YC)<49,49,49
49 ISLIC=LAST-IFIRST+1
C ISLIC=NO. OF SLICES WHOSE MID-ORDINATE IS CUT BY THE CIRCLE CONSIDERED
   IF(ISLIC>3)50,50,51
   IF(IFIRST-1)53,52,53
   IF(LAST-I1)55,54,55
55 PROCEED WITH ANALYSIS OF THIS CIRCLE
55 CENTRE=(X2(LAST)+D)C(LAST)/2.+(X2(IFIRST)-DX(IFIRST)/2.)/2.
   DO 602 I=IFIRST,LAST
   IF(CENTRE-X2(I))605,601,602
602 CENTRE=X2(I)
   H=Y(I,1)-C(I)
   GO TO 607
605 CENTRE=(X2(I-1)+X2(I))/2.
   H=((Y(I-1,1)-C(I-1))+(Y(I,1)-C(I)))/2.
607 FACTOR=-7.0
   CONST1=X2(IFIRST)-DX(IFIRST)/2.
   CONST2=X2(LAST)+DX(LAST)/2.
   SUMA=0.
   SUMB=0.
   DO 60 I=IFIRST,LAST
   IF(C(I)>Y(I,1))57,56,56
57 DIST1=X2(I)-DX(I)/2.-CONST1
   IF(DIST1+CONST1-CENTRE)391,391,392
391 AX1(I)=DIST1/(CENTRE-CONST1)
   GO TO 301
392 AX1(I)=(CONST2-(DIST1+CONST1))/(CONST2-CENTRE)
301 AX1(I)=AX1(I)-AX2(I)
   GO TO 308
302 AX2(I)=(DIST2+CONST2+CENTRE)/393,393,394
393 AX2(I)=DIST2/(CENTRE-CENTRE)
   GO TO 308
394 AX2(I)=(CONST2-(DIST2+CONST1))/(CONST2-CENTRE)
308 XNET(I)=AX1(I)-AX2(I)
   DO 58 J=1,NM
   IF(C(I)>Y(J+1,1))58,58,59
58 CONTINUE
59 WI=W(J,1)+(Y(J,1)-C(I))*DX(I)*S(J,1)
   TERM(C(I))=(YC-C(I))/R
   TERM(D(I))=S(J,3)*(XC-X2(I))/R
TERMT(I) = (XC - X2(I)) / (YC - C I))
TERMX(I) = XNET(I) * S(J,3)
TERME(I) = W1 * TERMT(I)
TERMA(I) = S(J,2) * DX(I) + S(J,3) * W1 * (1 - S(J,4))
SUMA = SUMA * S(J,2) * DX(I) / TERMC(I) + S(J,3) * W1 * (TERMC(I) - S(J,4))

60 SUMB = SUMB * W1 * (XC - X2(I))
C SUMB IS +VE IF CENTROID TO L. OF CENTRE (SLIP TO RIGHT)
SUMB = SUMB / R
IF(SUMB) 86, 85, 85
86 DO 87 I = IFIRST, LAST
TERMT(I) = -TERMT(I) WITH THE SIGN
TERME(I) = -TERME(I)
87 TERMD(I) = -TERMD(I) SLIP IS TO THE LEFT
SUMB = SUMB
C CENTROID TO R. OF CENTRE
85 F(O) = SUMA / SUMB
C NEGLECTS FORCES BETWEEN SLICES
DO 89 K1 = 1, 20
SUMC = 0.
SUMD = 0.
88 DO 88 I = IFIRST, LAST
D = TERMC(I) * F(K1 - 1) + TERMD(I)
SUMC = SUMC + TERMA(I) / D
89 CONTINUE
WRITE(2, 130) ZNC, HT, XC, YC, ISLIC, P(O), F(K1), K1
130 FORMAT(4(F4.0, 2X), I3, 3H \ , F6.3, 2H , F6.3, 2H , I3, 40H)
1 ITERATION UNSATISFACTORY(/
GO TO 888
91 F(M) = F(K1)
M = K1
919 AMAX(0) = FACTOR * H * H
L = 0
908 L1 = L + 1
L2 = L + 20
DO 821 L = L1, L2
SUMNUM = 0.
SUMDEN = 0.
411 DO 411 I = IFIRST, LAST
D1 = TERMC(I) * (TERMC(I) * F(K1) + TERMD(I))
SUMNUM = SUMNUM + (TERMA(I) + AMAX(L - 1) * TERMX(I)) / D1 - TERME(I) - AMAX(L - 1)
1 * XNET(I) * TERMT(I) FOR VERTICAL SIDE FORCES
411 SUMDEN = SUMDEN + TERMX(I) / D1 - XNET(I) * TERMT(I)
AMAX(L) = AMAX(L - 1) - SUMNUM / SUMDEN
IF(ABS(AMAX(L)) - AMAX(L - 1)) < 0.005) 812, 821, 821
821 CONTINUE
WRITE(2, 170) ZNC, HT, XC, YC, ISLIC, P(O), F(M), M
170 FORMAT(4(F4.0, 2X), I3, 3H \ , F6.3, 2H , F6.3, 2H , I3)
WRITE(2, 171) AMAX(0), AMAX(L), L, FACTOR
171 FORMAT(5H AMAX(0) = , F7.0, 9H AMAX L) =, F7.0, 3H L =, I3, 8H FACTOR =, F4.0,
123H AMAX(0) NOT SUITABLE/
FACTOR = FACTOR + 1.
GO TO 919
DO 902 K1=K2,K3
SUMC1=0.
SUMD1=0.
DO 903 I=IFIRST,LAST
G1=TERM1(I)+AMAX(L)*TERM2(I)
D2=TERM3(I)*F(K1-1)+TERM4(I)
SUMC1=SUMC1+G1/D2
903 SUMD1=SUMD1+G1*TERM2(I)/(D2*D2)
F(K1)=F(K1-1)*(1-(SUMB-SUMC1)/(SUMB-SUMD1))
IF(ABS(F(K1)-F(K1-1))<0.005)904,902,902
902 CONTINUE
GO TO 908

904 IF(K1 .GT. K2) GO TO 908
FK=F(K1)
CALL MOVETO(800,800,.TRUE.,0,7)
CALL RLDISP(FK,6,3,IGNORE)
CALL XHIBIT(FILE,1000)
888 CALL TRACK(IY,IX,ISTOP)
IF(ISTOP .LT. 0) GO TO 6011
CALL ACTION(IRAY)
IF(IRAY(2),EQ.48) GO TO 851
IF(IRAY(2),NE.56) GO TO 6011
MOVING=0
GO TO 444

851 WRITE(2,2144)ZNC,HT,IX,YC,ISLIC,F(0),F(M),F(K1),K1
214 FORMAT(F5.0,1H ,3(F4.0,2X),I3,3H ,F6.3,2H ,F6.3,2H ,I3,2H ,F6
1,3,2H ,I3)
WRITE(2,196)AMAX(0),AMAX(L),L,FACTOR
196 FORMAT(9H AMAX(0)=,F7.0,9H AMAX(L)=,F7.0,3H L=,I3,8H FACTOR=,F4.0/
1/)GO TO 6011
43 WRITE(2,350)ZNC,HT,IX,YC
350 FORMAT(F5.0,1H ,3(F4.0,2X),67H
1 CIRCLE CUTS BOTTOM CONTOUR/)
GO TO 888
46 WRITE(2,450)ZNC,HT,IX,YC
450 FORMAT(F5.0,1H ,3(F4.0,2X),58H
1 CIRCLE DOESN'T CUT/)
GO TO 888
48 WRITE(2,550)ZNC,HT,IX,YC
550 FORMAT(F5.0,1H ,3(F4.0,2X),75H
1 TOP CONTOUR CUTS UPPER SEMI CIRCLE/)
GO TO 888
50 WRITE(2,650)ZNC,HT,IX,YC,ISLIC
650 FORMAT(F5.0,1H ,3(F4.0,2X),I3,52H
1 TOO FEW SLICES/)
GO TO 888
52 C(I1+1)=YC-SQRT(R2-IX*IX)
IF(C(I1+1)=A 1,2,1))61,53,53
61 WRITE(2,750)ZNC,HT,IX,YC,ISLIC
750 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H
1 CIRCLE CUTS L.H. EDGE/)
GO TO 888

NEWTON'S RAPHSON ITERATION METHOD FOR FACTOR OF SAFETY GIVEN BY BISHOP'S RIGOROUS METHOD
54 C(I1+1)=YC-SQRT(R2-(X2(I1)-XC+DX(I1)*0.5)*(X2(I1)-XC+DX(I1)*0.5))
   IF(C(I1+1)-A(I1,JL1))>2,55,55
62 WRITE(",850)ZNC,HT,XC,YC,ISLIC
850 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H
   1 CIRCLE CUTS R.H. EDGE/)
GO TO 888
56 WRITE(2,950)ZNC,HT,XC,YC,ISLIC
950 FORMAT(F5.0,1H ,3(F4.0,2X),I3,59H
   1 CIRCLE CUTS TWICE/)
GO TO 888
28 RETURN
END
&RUN;