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Informational Report

SUPPORTING DOCUMENT FOR

PC STABL 4M

Jose E. Thomaz

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Informational Report
SUPPORTING DOCUMENT FOR
PC STABL 4M

TO: H. L. Michael, Director October 4, 1988
Joint Highway Research Project

FROM: C. W. Lovell, Research Engineer File 6-14-12
Joint Highway Research Project

The attached report is an informational one, for research funded outside the JHRP structure.

The slope stability program PC STABL 4 has been modified in accordance with the suggestions of users, and the result is PC STABL 4M. The principal modifications are in (1) the estimation of steady state flow pore pressures, and (2) the use of Janbu correction coefficients in the method of slices.

The information is of value to the IDOH, since they routinely use the STABL program.

Respectfully submitted,

C. W. Lovell
Research Engineer

Informational Report

SUPPORTING DOCUMENT

FOR

PC STABL 4M

by

Jose E. Thomaz

Graduate Assistant

Joint Highway Research Project

File No. 6-14-12

Prepared as Part of an Investigation

Conducted by

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I. INTRODUCTION

PCSTABL4M is a computer program written in FORTRAN source language for the general solution of two-dimensional slope stability problems using limiting equilibrium. The calculation of the factor of safety against instability of a slope is performed using either the simplified Bishop method, applicable to circular shaped failure surfaces or the simplified Janbu method, applicable to failure surfaces of general shape. Spencer's method, a full equilibrium method applicable to any type of surface is available in PCSTABL5M. The simplified Janbu method has an option to use a correction factor, developed by Janbu, which can be applied to the factor of safety to reduce the conservatism produced by the assumption of no interslice forces.

PCSTABL4M features unique random techniques for generation of potential failure surfaces for subsequent determination of the more critical surfaces and their corresponding factors of safety. Circular, sliding block or more general irregular surfaces may be generated and analyzed using random search techniques or specific input of the coordinates of a given potential failure surface. PCSTABL4M is programmed to handle heterogeneous soil systems, anisotropic soil strength properties, static groundwater and surface water, pseudo-static earthquake loading, surcharge boundary loading, and tieback loading.

The tieback loading feature provides for the input of horizontal or near horizontal tieback or line loads for analyzing the overall stability of tied-back or braced slopes and retaining walls. PCSTABL4M program is the only known computer program with the ability to analyze slopes subjected to tieback or concentrated loads using either the simplified Janbu or simplified Bishop method of slices.

Both on screen and plotted graphical output are provided as visual aids to confirm the correctness of problem input data. Program generated error messages pinpoint locations where input data are inconsistent with PCSTABL4M's input requirements. PCSTABL4M's free-form data input eases the task of preparing data, resulting in a reduction of input errors.

This manual is not intended to explain how PCSTABL4M functions or what assumptions are made to arrive at a solution. However explanations on the use of certain features of PCSTABL4M are presented. For a more detailed explanation of the logical operation of PCSTABL4M and

mathematical models employed refer to the JHRP Reports by the authors. "Computer Analysis of General Slope Stability Problems", JHRP-75-8, June 1975, "Computerized Slope Stability Analysis for Indiana Highways", JHRP-77-25, December 1977, "Slope Stability Analysis Considering Tiebacks & other Concentrated Loads", JHRP-86-21, and "STABL5... The Spencer Method Of Slices, Final Report", JHRP-85-17.

II. DEVELOPMENT OF STABL

The 2-D computer program STABL was developed at a time when most highway agencies analyzed slope stability using two common techniques: computer-aided, grid-type circular searches; and block analyzes for simple and specified surfaces. Circles were often assumed to be the appropriate shape for potential failure surfaces simply because there was no other shape which could be used for computerized searching.

In the last two decades, improvements in 2-D slope stability analysis have proceeded in several directions; one of these is contained in STABL, in the form of computerized searching with non-circular shapes. The non-circular routines RANDOM and BLOCK were first reported by Siegel (1975a) as well as a random (as opposed to a grid) type search with circles (CIRCL2). Favorable comparisons of the FOS values generated by STABL with those for the same surfaces by other methods of slices were reported by Boutrup (1977).

STABL was placed on line for routine use in 1976 by the Indiana Department of Highways (IDOH), and after being reported in the open literature (References 11, 2, 3, 4, 12), the program began to be adopted by many agencies. STABL has been modified in many ways over the past twelve years, and users of the program have helped greatly in debugging operations. The present version of STABL is called PCSTABL4M (written for micro-computers). It retains all the capabilities and options of the original one. In addition, it includes provision for the analysis of tied-back slopes.

Agencies staffed with appropriate mathematical and software skills can insert any desired slices solution into the program... simplified or total equilibrium. STABL is a stability analysis system, of which the method of slices detail, is a small part.

STABL values may be checked for a specific failure surface in several ways. CIRCL2 should yield about the same FOS (for the same circle) as any other computerized analysis for circles. To determine that this is indeed the case, the new user of STABL can run CIRCL2 in parallel with his present method. BLOCK or BLOCK2 can be checked approximately (for a specific block) either manually or perhaps by existing charts. RANDOM is amenable to approximate manual checks.

III. PROBLEM GEOMETRY

To start off, it is necessary to plot the problem's geometry to scale on a rectangular coordinate grid. Coordinate axes should be chosen carefully such that the total problem is defined within the first quadrant. This enables the graphical aspects of the program to function properly. In doing this, potential failure surfaces which may develop beyond the toe or the crest of the slope should be anticipated (Figure 1). Deep trial failure surfaces passing below the horizontal axis are not allowed, as well as, trial failure surfaces which extend beyond the defined ground surface in either direction. If any coordinate point defining the problem's geometry is detected by the program to lie outside the first quadrant, an appropriate error code is displayed and execution of STABL is later terminated.

Situations where the resulting plotted profile would be too small in scale to be useful for interpretation should be avoided (Figure 2). Figure 1 is an excellent example of well chosen coordinates where there is enough room for possible failure surface development, and the profile geometry is plotted to the largest scale possible within the allowed format. If these requirements are not considered before the input data are prepared, revision of the entire set of data could later become a necessity.

The ground surface and subsurface demarcations between regions of differing soil parameters are approximated by straight line segments. Any configuration can be portrayed so long as the sloping ground surface faces the vertical axis and does not contain an overhang. Vertical boundaries should be specified slightly inclined to the right for computational reasons (e.g., $X_{left} = 100.0, X_{right} = 100.1$).

Assigned with each surface and subsurface boundary is a soil type which represents a set of soil parameters describing

Figure 1: Extent of potential failure surfaces.

..

Coordinates Too Large in Comparison with Height and Length of Slope

Too Much Room Allowed Beyond the Toe and Crest of Slope in Comparison to its Height and Length

Figure 2: Scaling resulting from correct but inadequate definition of problem.

the area projected beneath. Vertical lines, passing through the end points of each boundary, bound the area in lateral extent. The area below a boundary may or may not be found at its bottom by another boundary beneath which different soil parameters would be defined (Figure 3).

The program requires a certain level of order by which boundary data are prepared. The boundaries may be assigned temporary index numbers for ordering by the following procedure. The ground surface boundaries are numbered first, from left to right consecutively, starting with (1). All subsurface boundaries are then numbered in any manner as long as no boundary lies below another having a higher number. That is, at any position which a vertical line might be drawn, the temporary index numbers of all boundaries intersecting that line must increase in numerical order from the ground surface downward. After all the boundaries have been temporarily indexed, the data for each boundary should be prepared in that order.

The data set describing a profile boundary line segment consists of X and Y coordinates of the left and right end points and a soil type number indicating the soil type beneath. The end points of each boundary are specified with the left point proceeding the right, and with the X coordinate of each point required to precede its complimentary Y coordinate.

IV. PIEZOMETRIC SURFACES

If the problem contains one or more piezometric surfaces which would intersect a potential failure surface, they can be approximated by a series of coordinate points connected by straight line segments. If used, the piezometric surfaces must be defined continuously across the horizontal extent of the region to be investigated for possible failure surfaces. It is wise to extend the piezometric surfaces as far in each lateral direction as the ground surface is defined, to insure meeting this last requirement (Figure 4). Data for the coordinate points must be ordered progressing from left to right. Each point on a piezometric surface is defined by a X and Y coordinate specified in that order.

The connecting line segments defining a piezometric surface may lie above the ground surface and also may lie coincident with the ground surface or any profile boundary. This enables expression of not only the ground water table but

Figure 3: Relationship of soil to boundaries.

Figure 4: Water surface defined across entire extent of defined problem.

also surfaces of seepage and still water surfaces of bodies of water such as lakes and streams. The option of defining several piezometric surfaces makes it possible to model conditions of artesian or perched water tables.

In early versions of STABL the pore pressure was calculated using a method referred in this manual as the "old method".

When a phreatic surface is specified the "old method" computes pore pressure based on hydrostatic pressure, i.e., the head is the vertical distance from the base of the slice to the phreatic surface immediately above (see Figure 5) (Siegel, 1975a; Siegel, 1975b; Boutrup, 1977). This is a conservative estimate increasing more in conservatism with a steeper sloping piezometric surface. This pressure head can be as much as 30% higher than the actual head when the piezometric surface is dipping at 35° (see Figure 6).

To overcome this conservatism a new method was proposed referred as the "perpendicular method". The perpendicular method approximates the equipotential line as a straight line from the base of the slice perpendicular to the line through the piezometric surface bounding the top of that slice (see Figure 5). However, this tends to produce nonconservative pore pressures, increasing more in nonconservatism with a steeper sloping piezometric surface. The pressure head can be as much as 10% lower than the actual head when the piezometric surface is dipping at 35° . (Figure 6).

Since the old method is increasing in conservatism with steeper phreatic surface and the perpendicular method is increasing in nonconservatism, the average value of the two would tend to control the degree of conservatism. The average value is conservative since the old method is much more conservative than the perpendicular method is nonconservative. The pressure head is about 9% higher than the actual head when the piezometric surface is dipping at 35° (Figure 6). All three models are available in PCSTABL4M.

When the water surface is above the ground surface, hydrostatic pressures generated by the elevated water surface are assumed to act upon the ground surface.

Figure 5: Methods of Pore Pressure Determination.

- 1 - 350 dipping piezometric surface
- 2 - 290 dipping piezometric surface
- 3 - 170 dipping piezometric surface

- 4 - PCSTABL4 method of pore pressure determination
- 4M - PCSTABL4M method of pore pressure determination
- P - Perpendicular method of pore pressure determination
- A - Actual pore pressure

Figure 6: Handplot of flownet/Slope.

V. BOUNDARY LOADS

Uniformly distributed boundary loads applied to the ground surface are specified by defining their extent, intensity, and direction of application (Figure 7). The limiting equilibrium model used for analysis treats the boundary loads as strip loads of infinite length. The major axis of each strip load is normal to the two-dimensional X-Y plane within which the geometry of slope stability problems is solved. Therefore, the extent of a boundary load is its width in the two-dimensional plane.

Data for each boundary load consist of the left and right X coordinates which define the horizontal extent of load application, the intensity of the loading, and its inclination. The intensity specified should be in terms of the load acting on a horizontal projection of the ground surface rather than the true length of the ground surface. Inclination is specified positive counterclockwise from the vertical. The boundaries must be ordered from left to right and are not allowed to overlap.

A boundary load whose intensity varies with position can be approximated by substituting a group of statically equivalent uniformly distributed loads which abut one another. The sum of the widths of the substitute loads should equal the width of the load being approximated. The inclinations should be equivalent, and the intensities of substitute loads should vary as does the load being approximated.

VI. EARTHQUAKE LOADING

The use of earthquake coefficients allows for a pseudo-static representation of earthquake effects within the limiting equilibrium model. A direct relationship is assumed to exist between the pseudo-static earthquake force acting on the sliding mass and the weight of the sliding mass. specified horizontal and vertical coefficients are used to scale the horizontal and vertical components of the earthquake force relative to the weight of the sliding mass. Positive horizontal and vertical earthquake coefficients indicate that the horizontal and vertical components of the earthquake force are directed leftward and upward, respectively. Negative coefficients are allowed.

Figure 7: Definition of surcharge boundary loads.

The inertial forces due to the seismic coefficients are at the center of gravity of each slice. These forces do not change the pre-earthquake static pore pressures in the slope. If significant excess pore pressures changes or loss of shear strength is expected, or in the case of a "high risk" slope, a complete dynamic analysis should be performed. Examples of slope stability analysis encountering pseudo-static earthquake loads are described in JHRP-77-25, Section 4.5.4.

VII. SOIL PARAMETERS

Each soil type is described by the following set of isotropic parameters: the moist unit weight, the saturated unit weight, the Mohr-Coulomb strength intercept, the Mohr-Coulomb strength angle, a pore pressure parameter, a pore pressure constant, and an integer representing the number of the piezometric surface that applies to this soil.

The moist unit weight and the saturated unit weight are total unit weights, and both are specified to enable STABL to handle zones divided by a water surface. In the case of a soil zone totally above the water surface, the saturated unit weight will not be used, however, some value must be used for input regardless. Any value including zero will do. Similarly for the case where a soil zone is totally submerged, the moist unit weight will not be used. Again some value must be used for input.

Either an effective stress analysis (σ' , c') or total stress analysis (c , $\phi=0$) may be performed by using the appropriate values for the Mohr-Coulomb strength parameters.

Excess pore water pressure due to shear can be assumed to be related to the overburden by the single parameter r_u . The overburden does not include surcharge boundary loads. The pore pressure constant u_c of a soil type defines a constant pore pressure for any point within the soil described. Either or both of these two options for specifying pore pressures may be used, in combination with pore pressure related to a specified piezometric surface, to describe the pore pressure regime.

Soil types exhibiting anisotropic strength properties are described by assigning Mohr-Coulomb strength parameters to discrete ranges of direction. The strength parameters would vary from one discrete direction range to another.

The orientation of all line segments defining any potential failure surface can be referenced with respect to their inclination entirely within a range of direction between -90° and $+90^\circ$ with respect to horizontal. Therefore, the selection of discrete ranges of direction is confined to these limits. The entire range of potential orientation must be assigned strength values.

Each direction range of an anisotropic soil type is established by specifying the maximum (counterclockwise) inclination α_1 of the range (Figure 8). The data consist of this inclination limit and the Mohr-Coulomb strength angle and strength intercept for each discrete range. Data for each discrete range are required to be prepared progressing in counterclockwise order, starting with first range from -90° to α_1 (specifying α_1 as counterclockwise direction limit). The process is repeated for each soil type with anisotropic strength behavior.

VIII. CONCEPT OF SEARCHING ROUTINES

STABL can generate any specified number of trial failure surfaces in random fashion. The only limitation is computation time. Usually 100 surfaces are adequate. Each surface must meet specified requirements. As each acceptable surface is generated, the corresponding factor of safety is calculated. The ten most critical are accumulated and sorted by the values of their factors of safety. After all the specified number of surfaces are successfully generated and analyzed, the ten most critical surfaces are plotted so the pattern may be studied.

If the pattern is compact such that the ten most critical surfaces form a thin zone, and if the range in the value of the factor of safety for these ten surfaces is small, an additional refined search would be unnecessary. However, if just the opposite is true, an additional search with stricter surface requirements would then be necessary. There are two exceptions to this last case. The first is when one, some, or all of the ten most critical surfaces have a factor of safety below a value of 1, or perhaps a criterion the user has established. The second is when the most critical surface has a very large value for the factor of safety, much greater than the criterion for acceptance, and it is obvious that further refinement of a search for a more

Figure 8: Strength assignment to four discrete direction ranges

critical surface will not produce a value of the factor of safety less than the established criterion.

Circular and Irregular Surfaces

The searching routines which generate circular and irregular shaped trial failure surfaces are basically similar in use, and are therefore discussed together.

Trial failure surfaces are generated from the left to the right. Each surface is composed of a series of straight line segments of equal length, except for the last segment which most likely will be shorter. The length used for the line segments is specified.

Generation of an individual trial failure surface begins at an initiation point on the ground surface. The direction, to which the first line segment defining the trial failure surface will extend, is chosen randomly between two direction limits. An angle of 5° less than the inclination of the ground surface to the right of the initiation point would be one limit, while an angle of -45° to the horizontal would be another limit (Figure 9). The first line segment can fall anywhere between these two limits, but the random technique of choosing its position is biased so that it will lie closer to the -45° limit more often than the other.

By specifying zero values for both of the direction limits, the direction limits as described above are automatic. However, the counterclockwise and clockwise direction limits, instead of being calculated under STABL's direction, may be specified. After a preliminary search for the critical surface, it is usually found that all or most of the ten most critical surfaces have about the same angle of inclination for the initial line segments. By restricting the initial line segment within direction limits having a directional range smaller than that which would be used automatically by STABL, and at inclinations which would bracket the initial line segments of surfaces previously determined to be critical, subsequent searches can be conducted more efficiently.

After establishment of the first line segment, a circular shaped trial failure surface is generated by changing the direction of each succeeding line segment by some constant angle (Figure 10) until an intersection of the trial failure surface with the ground surface occurs. In effect, the chords of a circle are generated rather than the circle

Figure 9: Generation of first line segment.

Figure 10: Circular surface generation.

itself. The constant angle of deflection is obtained randomly.

An irregular shaped surface is generated somewhat differently after establishment of the first line segment. The direction of each succeeding line segment is chosen randomly within limits determined by the direction of the preceding line segment. Surfaces with reverse curvature are likely, and if a very short length is used for the line segments, a significant amount of kinkiness in the surfaces will be inevitable. Some reverse curvature is desirable but extreme kinkiness is not. To avoid the second case the length of the line segment selected should in general not be shorter than $1/4$ to $1/3$ the height of the slope.

When using either of these generation techniques to search for a critical failure surface, the following scheme is employed. STABL directs computation of a specified number of initiation points along the ground surface. The initiation points are equally spaced horizontally between two specified points, which are the leftmost and rightmost initiation points. Only the X coordinates of these two points, specified in left-right order, are required. From each initiation point, a specified number of trial failure surfaces are generated. If the left point coincides with the right, a single initiation point results, from which all surfaces are generated. The total number of surfaces generated will equal the product of the number of initiation points and the number of surfaces generated from each.

Termination limits are specified to minimize the chance of proceeding with a calculation of the factor of safety for an unlikely failure surface. If a generated trial failure surface terminates at the ground surface short of the left initiation limit (Figure 11), the surface is rejected prior to calculation of a factor of safety and a replacement is generated. If a generating surface goes beyond the right termination limit, it will be rejected requiring a replacement. The termination limits are also specified in left-right order.

A depth limitation is imposed by specifying an elevation below which no surface is allowed to extend. This is used, for example, to eliminate calculation of the factor of safety for generated surfaces that would extend into a strong horizontal bedrock layer. When a shallow failure surface is expected, the use of the depth limitation prevents generation and analysis of deep trial failure surfaces.

Figure 11: Trial failure surface acceptance criteria.

An additional type of search limitation may be imposed to handle situations such as variable elevation of bedrock or delimitating a weak zone and confining the search for a critical surface to that area, through use of the LIMITS command.

Sliding Block Surfaces

A sliding block trial failure surface generator provides a means through which a concentrated search for the critical failure surface may be performed within a well defined weak zone of a soil profile.

In a simple problem involving a sliding block shaped failure face (Figure 12), the following procedure is used. Two boxes are established within the weak layer with the intent that from within each, a point will be chosen randomly. The two points once chosen define a line segment which is then used as the base of the central block of the sliding mass. Any point within each box has equal likelihood of being chosen. Therefore, a random orientation, position and width of the central block is obtained. The boxes are required to be parallelograms with vertical sides. The top and bottom of a box may have any common inclination. Each box is specified by the length of its vertical sides and two coordinate points which define the intersections of its centerline with its vertical sides (Figure 13).

After the base of the central block is created, the active and passive portions of the trial failure surface are generated using line segments of equal specified length by techniques similar to those used by the circle and irregular trial failure surface generators.

Starting at the left end of the central block's base, a line segment of specified length is randomly directed between the limits of 0° and 45° with respect to the horizontal (Figure 14). The chosen direction is biased towards selection of an angle closer to 45° . This process is repeated as necessary until intersection of a line segment with the ground surface occurs, completing the passive portion of the trial surface.

For the active portion of the trial failure surface, a similar process is used with the limits for selection of the random direction being 0° and 45° with respect to the

Figure 12: Simple sliding block problem.

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Figure 13: Sliding block box specification.

Figure 14: Generation of active and passive sliding surfaces.

vertical (Figure 14). The chosen direction is biased towards selection of an angle nearer 45° .

A modified version of the sliding block surface generator, named BLOCK2, generates active and passive portions of the sliding block surface according to the Rankine theory. To avoid the problem of the active or passive wedges terminating out of the defined slope boundaries sketches should be drawn.

PCSTABL4M allows the use of more than two boxes for the formation of the central block (Figure 15). The search may be limited to an irregularly shaped weak zone this way. Another application might be to conduct a search within a zone previously defined as being critical by use of the analysis command RANDOM.

Degenerate cases of parallelogram boxes are permitted. For example, if both points specified as the intersections of a parallelogram's centerline with its vertical sides are identical, and the length of the parallelogram's vertical sides is non-zero, then a vertical line segment, in effect, is defined. When a trial failure surface is generated, each point along the vertical line segment's length has an equal likelihood of becoming a point defining the surface. The vertical line segment could further degenerate into a point if a zero value is specified for the length of the parallelogram's vertical sides.

Then all surfaces generated would pass through the single point. One more case of a degenerate parallelogram is a line segment whose inclination and position is that of the parallelogram's centerline. For this case, the length of the vertical sides is zero but the intersections of the parallelogram's centerline with its vertical sides are not identical. Again, any point along the length of the line segment has equal likelihood of becoming a point defining a generated trial failure surface.

Individual Failure Surface

If the failure of the slope is being studied and the location of the actual failure surface is known, STABL offers the option of specifying the known surface as an individual surface for analysis. Another situation for which this option would be useful is when the geologic pattern and shear strength data indicate one or more well defined weak paths along which failure would be expected to occur.

Intensive Search of Critical Zone Previously
Defined by CIRCLE or RANDOM

Search in Irregular Weak Layer

Figure 15: Sliding block generator using more than two boxes.

An individual failure surface is approximated by straight line segments defined by a series of points. The end points of the specified trial failure surface are checked for proper location within the horizontal extent of the defined ground surface. The Y coordinates for these two points need not be correctly specified. STABL directs the calculation of the Y coordinate, for each of these two points, from the intersection of a vertical line defined by the specified X coordinate and the ground surface. Data for the coordinate points must be ordered from left to right.

Surface Generation Boundaries

As an additional criterion for acceptance of generated trial failure surfaces, an ability to establish boundaries through which a surface may NOT pass has been provided. Such boundaries may be used with all surface generating routines except BLOCK2. Each generation boundary specified is defined by two coordinate points. If a generating surface intersects the line segment defined by the pair of coordinate points, it will either be rejected and a replacement surface will be generated, or the surface will be deflected so that it may be successfully completed. The amount of deflection permitted for a trial failure surface is limited, and when it is insufficient to clear the surface generation boundary intersected, the surface is rejected.

When specifying surface generation boundaries the coordinate points of the left end point should precede those of the right end point. For the case of vertical boundaries, the order is not important. Along with the total number of boundaries, the number of them which deflect generating surfaces upward is specified. The data for these boundaries are required to precede the data for boundaries that deflect downward.

As mentioned previously, a variable elevation bedrock surface can be bounded so that no generated surfaces will pass through the rock. For this case, all the surface generation boundaries defining the bedrock surface would be specified to deflect intersecting trial failure surfaces upward. Another use might occur after a critical zone has been roughly defined by a searching technique. This zone could be bound so that the subsequent search will be completely confined to it. Surface generation boundaries above the zone would be specified to deflect downward, and those below the zone upward.

An important consideration that should be given whenever any type of limitation is imposed for conducting a search for a critical surface is how many generating surfaces are likely to be rejected. A rejected surface is lost effort regardless of how efficiently it was generated by STABL. Perhaps for example, a multiple box search using command BLOCK would be more efficient than using RANDOM with strict limitations.

IX. TIEBACK LOADS

The use of tiebacks in geotechnical engineering and construction for stability of slopes and support of excavations has increased substantially within the last several years. As a result, the need for a method of analyzing the overall stability of slopes and retaining walls subjected to horizontal or inclined concentrated loads has become more evident. Before the development of (PC) STABL4 (M), the input of horizontal or inclined concentrated loads acting on a near vertical slope was somewhat difficult in STABL. In addition the factor of safety was not formulated for this type of loading and thus, did not fully account for the distribution of force to the failure surface caused by concentrated boundary loads.

Therefore, to increase the versatility of STABL, new routines have been created within STABL to permit input of horizontal or inclined concentrated loads. These routines were created specifically for the input of tieback loads but may be easily used for any type of concentrated load applied to the ground surface. The latest versions of STABL, (PCSTABL4M and PCSTABL5M) contain the new routines which utilize Flamant's Formulas as proposed by Morlier and Tenier (1982) and the simplified Bishop method of analysis for circular failure surfaces, and the simplified Janbu method of analysis for non-circular failure surfaces. The tieback option may be used with either random or specific failure surface generation methods for irregular, block or circular failure surfaces.

Tieback or other types of concentrated loads are input by specifying the ground surface boundary number where the load is to be applied, the Y coordinate of the point of application of tieback load, the load per tieback, the horizontal spacing between tiebacks, the inclination of tieback load as measured clockwise from the horizontal plane, and the free length of tieback (Figure 16). For concentrated boundary loads such as strut loads in a braced

excavation which do not extend into the ground like tiebacks, the length of the tieback is zero. An equivalent line load is calculated for each tieback load specified assuming a uniform distribution of load horizontally between point loads. The current version of STABL (PCSTABL4M) can allow for the input of concentrated loads applied to a horizontal ground surface boundary, and also allow concentrated loads to be inclined between 0 and 180 degrees from the horizontal.

Description of New Tieback Routines

Unlike other slope stability programs, PCSTABL4M distributes the force from a concentrated load throughout the soil mass to the whole failure surface and hence to all slices of the sliding mass. Other slope stability programs on the other hand, only take a concentrated load into account on the slice on which it acts. This distribution of load throughout the soil mass is a unique feature of PCSTABL4M.

First an equivalent line load is calculated for a row of tiebacks by dividing the specified tieback load (point load) by the corresponding horizontal spacing between tieback loads. The resulting line load is called TLOAD, (Figure 17), and is inclined from the horizontal by an angle INCLIN. The radial stress on the midpoint of a slice is calculated using Flamant's Formula (Morlier and Tenier, 1982):

$$\sigma_r = [2(TLOAD) \cos(TTHETA)] / [\pi (DIST)]$$

where:

σ_r = Radial stress

TLOAD = Equivalent tieback line load

TTHETA = Angle between the line of action of the tieback and the line between the point of application of the tieback on the ground surface and the midpoint of the slice.

DIST = Distance between the point of application of the tieback on the ground surface and the midpoint of the slice.

TIEBACK INPUT PARAMETERS

②

- Ground surface boundary number where tieback load is applied
- X coordinate of point of application (ft) or (m)
- Y coordinate of point of application (ft) or (m)
- P Magnitude of load per tieback (lbs) or (kg)
- H Horizontal spacing between tiebacks (ft) or (m)
- I Inclination of tieback load (deg)
- L Free length of tieback (ft) or (m)

Figure 16: Tieback input parameters.

Figure 17: Transfer of concentrated load to failure surface.

The radial force, PRAD, at the midpoint of the base of the slice due to the concentrated load is calculated by multiplying the radial stress by the length of the base of the slice:

$$PRAD = [2(TLOAD) \cos(TTHETA) (DX)] / [\pi(DIST) \cos(ALPHA)]$$

where:

PRAD = Radial force on base of slice due to concentrated load.

ALPHA = Inclination of base of slice

DX Slice width

Note that the radial stress produced on the base of the slice by the concentrated load is proportional to the load applied (TLOAD) and the width of the slice (DX), inversely proportional to the distance between the point of application of the load and the midpoint of the base of the slice (DIST), and dependent upon the angle between the line of action of the load and the line between the point of application of the load and the midpoint of the base of the slice (TTHETA). Therefore, slices which are in line with the direction of the concentrated load will receive a larger portion of the total load than will slices which are farther away and whose angle TTHETA is large.

The radial force PRAD is distributed in the same manner to all the slices of the sliding mass. The radial forces on all the slices are then summed in the direction of the concentrated load, PSUM, and compared with the applied load, TLOAD. Since the sum of radial forces for a failure surface, PSUM, is not always exactly equal to the applied load due to slope geometry and the shape of the failure surface, the radial force applied to the base of each slice is modified as follows:

$$PRAD = TLOAD/PSUM$$

The refined radial force for each slice, PRAD, is broken into its components normal and tangential to the base of the slice for calculation of the factor of safety. The normal and tangential components of the force due to the concentrated load are respectively:

$$PNORM = (PRAD) \cos(ALPHA1)$$

$$PTAN = (PRAD) \sin(ALPHA1)$$

The same process is repeated for all additional rows of tiebacks. The sum of the normal components and the sum of the tangential components due to all rows of tiebacks are then used in the slice equilibrium equations for calculating the factor of safety.

There is a special case where the tieback loads will not be distributed to quite all the slices of the sliding mass and is shown in Figure 18. Figure 18 shows the limit of the stress distribution for a benched slope. The force due to the applied load is not distributed to the slices of the far left or the slices of the far right since this would require distribution of load through air and not the soil mass.

TIES input Restrictions

The point of application of a tieback on the ground surface may not be at a ground surface boundary node. Use a slight offset from the node, (i.e. 70.01 instead of 70).

No more than 10 tieback loads can be specified; however, they can be in any order. The inclination of a tieback must be equal to or greater than zero degrees and less than 180 degrees as measured clockwise from the horizontal.

The horizontal spacing between tiebacks must be greater than or equal to 1 ft (or 1 meter if using SI units).

The length of a tieback must be equal to or greater than zero ft. Zero is used for loads other than tieback type of loads.

X. DATA PREPARATION

A primary goal during the development of program STABL, was to maintain a simple format for data preparation and input. This was felt to be very important because much time can be

Figure 18: Limit of stress distribution due to concentrated load.

consumed getting the "bugs" out of the input data, especially by a new or occasional user.

In an attempt to reduce preparation errors and debugging time, STABL has four helpful features: (1) problem oriented language; (2) free-form data input; (3) execution time data consistency checking; and (4) graphical display of input and output geometry data. These features will be discussed in following sections.

Problem Oriented Language

This feature allows the selection, by command, of only those portions of STABL which are required to solve a particular problem. It also provides flexibility in problem modification for additional analyses during a single execution of STABL.

Below are listed the commands understood by STABL and their primary functions. There are essentially two types; data commands and analysis commands.

Data Commands:

PROFIL	initiate problem; read and store boundary data defining ground surface and subsurface material interfaces.
SOIL	read, check, and store isotropic soil parameter data.
ANISO	read, check, and store anisotropic strength parameter data.
WATER	read, check and store data defining piezometric surfaces.
SURFAC or SURBIS	read, check, and store data defining a single trial failure surface (SURBIS only for circular shaped failure surfaces).
LOADS	read, check, and store data defining surface boundary surcharge loads.
EQUAKE	read and store pseudo-static earthquake coefficients and cavitation pressure.

LIMITS read, check, and store data defining surface generation boundaries.

TIES read, check, and store data defining tieback loads.

Analysis Commands:

EXECUT calculate factor of safety for single specified trial failure surface.

CIRCLE or

CIRCLE2 generate circular surfaces and determine critical surfaces.

RANDOM generate irregular surfaces and determine critical surfaces.

BLOCK or

BLOCK2 generate sliding block surfaces and determine critical surfaces.

The data commands' primary functions are to read data pertinent to the definition of a particular slope stability problem, to check the data for consistency with program requirements, and to store these data for subsequent use by the analysis commands.

The analysis commands' primary purpose is analysis of the problem in some manner using previously stored data. One such way is the analysis of a single trial failure surface previously defined by the data command SURFAC. Another way is to generate potential failure surfaces, searching for the critical surfaces, using one or more of the surface generation techniques.

General Rules for Use of Commands

All commands may be used as often as desired, however, there are some restrictions that are imposed regarding sequencing them for execution.

Once a data command is invoked, the data, stored as a result, remain in effect until replacement or suppression is effected by another usage of the same command. There are two exceptions to this. The first concerns the use of command PROFIL. The command prepares STABL for a new problem by

defining a new profile. As a result, all data, which may have been stored by previous usages of other data commands in the execution sequence, will be lost. Incidentally, PROFIL is required to be the first command in the execution sequence. The second exception involves use of the analysis commands CIRCLE, BLOCK and RANDOM. Use of these commands will destroy the trial failure surface data stored by command SURFAC.

Temporary suppression of data previously stored by any of the commands WATER, LOADS, LIMITS, ANISO, and TIES is accomplished by a special use of each command. Each of the commands require that the number of repetitive data sets be specified. By specifying zero, STABL is instructed to suppress all data pertinent to the particular command used. While suppressed, the data are not available for use by the analysis commands. The data will remain suppressed until reactivated by a second use of the same command with zero specified. If new data are read and stored while old data are suppressed, the old data are lost for further use.

Isotropic soil parameters may be modified by specifying the number zero and the number of soil types which are to be changed. Then the soil type number and appropriate soil parameters are specified for each soil type modified.

Use of the analysis commands requires, as a minimum, definition of a problem's profile and the soil parameters. In addition, use of the analysis command EXECUT requires definition of a specific trial failure surface.

Below is an example of how some commands might be sequenced.

PROFIL	.. data (1)	
SOIL	.. data (2)	
SURFAC	.. data (3)	
EXECUT	Factor of safety calculation	with data (1), (2), and (3).
WATER	.. data (4)	
EXECUT	Factor of safety calculation	with data (1), (2), (3), and (4).
SURFAC	.. data (5)	Replaces data (3) with data (5).

EQUAKE .. data (6)

EXECUT Factor of safety calculation with data (1), (2), (4), (5), and (6).

WATER .. suppress data (4)

EXECUT Factor of safety calculation with data (1), (2), (5), and (6).

WATER .. reactivate data (4)

EQUAKE .. data (7) Replace data (6) with data (7).

EXECUT Factor of safety calculation with data (1), (2), (4), (5), and (7).

PROFIL .. data (8) Nullifies all previous data-initiates new problem.

EQUAKE .. data (9)

SOIL .. data (10)

SURFAC .. data (11)

EXECUT Factor of safety calculation with data (8), (9), (10), and (11).

Free-Form Data Input

To ease requirements of data input, a method for reading numbers free-form has been incorporated within STABL. All commands should commence on the first column of individual lines. When the computer cannot match your command with one which STABL has been programmed to recognize, your command will be displayed with an error message as output and execution will be terminated. Be certain the spelling of each command is correct.

Each line containing numerical data should be entered such that the first data item commences on the first column. One and only one blank space should separate each subsequent data item on a line. STABL directs the computer to read data from the next line when two or more blank spaces are encountered. If a gap of more than one blank space occurs between two adjacent data items, all data items on the line following the gap will not be read. Instead, data on the following line will be read next. If unintentional, a shift in all data subsequently read will occur. Eventually, an

indirect error will be generated. Most likely is a situation where a real number is read as an integer or vice verse.

An integer is a whole number generally used for counting, while a real number is a rational number used for measurement of magnitude. STABL requires that an integer contains no decimal point, while a real number must.

For the problem description associated with the data command PROFIL, any combination of alpha-numeric characters, blanks, and special characters may be used within the eighty columns of one line. The description will appear on two lines as printed output of forty columns each, so the description should be written accordingly.

XI. INPUT GUIDE

The following table detail the data input requirements for PCSTABL4M. Each table describes the input necessary to enter, modify, suppress or reactivate the data associated with a command. The first line on the table gives the Command Card information, consisting of the Command Code, i.e., PROFIL. The data associated with that command follows. Each "DATA CARD" corresponds to a new line in the input file. The data to be input on a Data Card are described and listed in the order that they appear on the line together with the data type (integer or real). For example, the second line after a PROFIL Command is the data card containing (in order) the total number of boundaries and the number of surface boundaries. Both these data are integers.

INPUT FOR PROFILE

COMMAND CARD PROFIL Command Code

DATA CARD	Title	
DATA CARD	Integer	Total number of boundaries
	Integer	Number of surface boundaries
DATA CARD	Real	X coordinate of left end of boundary
(ft)		
	Real	Y coordinate of left end of boundary
(ft)		
	Real	X coordinate of right end of boundary
(ft)		
	Real	Y coordinate of right end of boundary
(ft)		
	Integer	Soil type index number for material immediately beneath boundary.

NOTE: Repeat proceeding data card for each boundary.

INPUT FOR SOIL TYPES

COMMAND CARD	SOIL	Command Code
DATA CARD	Integer	Number of soil types
DATA CARD	Real	Moist unit weight (pcf)
	Real	Saturated unit weight (pcf)
	Real	Isotropic strength intercept (pcf)
	Real	Isotropic strength angle ()
	Real	Pore pressure parameter
	Real	Pore pressure constant (pcf)
	Integer ¹	Piezometric surface number

NOTE: Repeat proceeding data card for each soil type.

1. If no piezometric surface is specified, any number can be used.

INPUT FOR MODIFYING SOIL TYPES
(if specified)

COMMAND CARD	SOIL	Command Code
DATA CARD	Integer	Number zero (0)
	Integer	Number of soil types to be modified
DATA CARD	Integer	Soil type number
	Real	Moist unit weight (pcf)
	Real	Saturated unit weight (pcf)
	Real	Isotropic strength intercept (psf)
	Real	Isotropic strength angle ()
	Real	Pore pressure parameter
	Real	Pore pressure constant (psf)
	Integer ¹	Piezometric surface number

NOTE: Repeat proceeding data card for each soil type modified.

1. If no piezometric surface is specified, any number can be used.

INPUT FOR STRENGTH ANISOTROPY

(if specified)

COMMAND CARD ANISO	Command Code
DATA CARD Integer	Number of anisotropic soil types
DATA CARD Integer	Soil type index number
Integer	Number of directional strength parameter data sets

NOTE: Repeat proceeding data card and the following set of data cards for each anisotropic soil type.

DATA CARD Real	Counterclockwise direction limit ()
Real	Strength intercept (psf)
Real	Strength angle ()

NOTE: Repeat proceeding data card for each range of direction

INPUT FOR SUPPRESSING OR REACTIVATING STRENGTH ANISOTROPY

(if specified)

COMMAND CARD ANISO	Command Code
DATA CARD Integer	Number zero (0)

INPUT FOR WATER SURFACE

(if specified)

COMMAND CARD WATER	Command Code
DATA CARD Integer	Number of piezometric surfaces defined.
Integer	Porepressure Model (1 for Hydrostatic, 2 for Perpendicular or 3 for Average) ²
Real	Unit weight of water ³

NOTE: Repeat the following set of data cards for each piezometric surface.

DATA CARD Integer	Number of points defining the water surface.
DATA CARD Real	X coordinate of point on water surface (ft).
Real	Y coordinate of point on water surface (ft).

NOTE: Repeat proceeding data card for each point on the water surface.

2. See appendix 1.

3. If 0. is specified, 62.4 (pcf) is assumed.

INPUT FOR SUPPRESSING OR REACTIVATING WATER SURFACE
(if specified)

COMMAND CARD	WATER	Command Code
DATA CARD	Integer	Number zero (0)

INPUT FOR BOUNDARY LOADS
(if specified)

COMMAND CARD	LOADS	Command Code
DATA CARD	Integer	Number of boundary loads
DATA CARD	Real	X coordinate of left end of boundary load (ft).
load	Real	X coordinate of right end of boundary load (ft).
	Real	Intensity of boundary load (psf)
	Real	Angle of inclination of boundary load positive counterclockwise from vertical ().

NOTE: Repeat proceeding data card for each boundary load.

INPUT FOR SUPPRESSING FOR REACTIVATING BOUNDARY LOADS
(if specified)

COMMAND CARD	LOADS	Command Code
DATA CARD	Integer	Number zero (0)

INPUT FOR EARTHQUAKE LOAD
(if specified)

COMMAND CARD EQUAKE Command Code
DATA CARD Real Earthquake coefficient for horizontal
 acceleration (defined positive outwards
 from face of slope³)
 Real Earthquake coefficient for vertical
 acceleration (defined positive upwards³)
 Real Cavitation pressure (psf)

3. Negative values may be specified.

INPUT FOR SPECIFIC FAILURE SURFACE
(if specified)

COMMAND CARD SURFAC Command Code (or SURBIS⁴)
DATA CARD Integer Number of points defining the failure
 surface
DATA CARD Real X coordinate of point on failure surface
 Real Y coordinate of point on failure surface

NOTE: Repeat proceeding data card for each point on the failure surface.

4. SURBIS for circular surfaces, Modified Bishop Factor of Safety.

INPUT FOR ANALYSIS OF SPECIFIED TRIAL SURFACE
(if specified)

COMMAND CARD EXECUT Command Code

INPUT FOR TRIAL SURFACE GENERATION LIMITS
(if specified)

COMMAND CARD LIMITS Command Code
DATA CARD Integer Total number of generation boundaries
 Integer Number of generation boundaries which
 deflect upward
DATA CARD Real X coordinate of left end of generation
 boundary (ft)
 Real Y coordinate of left end of generation
 boundary (ft)

Real X coordinate of right end of generation
boundary (ft)
Real Y coordinate of right end of generation
boundary (ft)

NOTE: Repeat proceeding card of each generation boundary.

INPUT FOR SUPPRESSING OR REACTIVATING TRIAL SURFACE
GENERATION LIMITS
(if specified)

COMMAND CARD LIMITS Command Code
DATA CARD Integer Number zero (0)

INPUT FOR CIRCULAR SURFACE SEARCHING.
(if specified)

JANBU'S METHOD

COMMAND CARD CIRCLE
DATA CARD Integer 0 (No), 1 or 2 (Yes) To use Janbu's
 empirical coefficient
Integer Soil fits (if above is 1):
 1 - $\emptyset = 0$
 2 - $c \ \& \ \emptyset$ both > 0
 3 - $c = 0$
 (else if above is 2):
Real K user's value for Janbu's equation (appendix 1)
DATA CARD Integer Number of initiation points
Integer Number of surfaces to be generated from
 each initiation point
DATA CARD Real X coordinate of leftmost initiation point (ft)
Real X coordinate of rightmost initiation point (ft)
Real X coordinate of left termination limit (ft)
Real X coordinate of right termination limit (ft)
DATA CARD Real Minimum elevation of surface development (ft)
Real Length of segments defining surfaces (ft)
Real Counterclockwise direction limit for
 surface initiation ()
Real Clockwise direction limit for surface
 initiation ()

BISHOP'S METHOD

COMMAND CARD CIRCL2
DATA CARD Integer Number of initiation points
Integer Number of surfaces to be generated from
 each initiation point

DATA CARD Real X coordinate of leftmost initiation point (ft)
 Real X coordinate of rightmost initiation point (ft)
 Real X coordinate of left termination limit (ft)
 Real X coordinate of right termination limit (ft)
 DATA CARD Real Minimum elevation of surface development (ft)
 Real Length of segments defining surfaces (ft)
 Real Counterclockwise direction limit for surface initiation ()
 Real Clockwise direction limit for surface initiation initiation.

INPUT FOR IRREGULAR SURFACE SEARCHING
 (if specified)

COMMAND CARD RANDOM Command Code
 DATA CARD Integer 0 (No), 1 or 2 (Yes) To using Janbu's empirical coefficient
 Integer Soil fits (if above is 1):
 1 - $\emptyset = 0$
 2 - $c \ \& \ \emptyset$ both > 0
 3 - $c=0$
 (else if above is 2):
 Real K user's value for Janbu's equation (appendix 1)
 DATA CARD Integer Number of initiation points
 Integer Number of surfaces to be generated from each initiation point
 DATA CARD Real X coordinate of leftmost initiation point (ft)
 Real X coordinate of rightmost initiation point (ft)
 Real X coordinate of left termination point (ft)
 Real X coordinate of right termination point (ft)
 DATA CARD Real Minimum elevation of surface development (ft)
 Real Length of segments defining surfaces (ft)
 Real Counterclockwise direction limit for surface initiation ()
 Real Clockwise direction limit for surface initiation initiation
 ()

INPUT FOR BLOCK SURFACE SEARCHING
 (if specified)

COMMAND CARD BLOCK Command Code (or BLOCK2⁵)
 DATA CARD Integer 0 (No), 1 or 2 (Yes) To use Janbu's empirical coefficient
 Integer Soil fits (if above is 1):
 1 - $\emptyset = 0$
 2 - $c \ \& \ \emptyset$ both > 0
 3 - $c=0$
 (else if above is 2):
 Real K user's value for Janbu's equation (appendix 1)

DATA CARD Integer Total number of surfaces to be generated
 Integer Number of boxes used to generate base of
 central block
 Real Length of segments defining surfaces (ft)
 DATA CARD Real X coordinate of left end of centerline
 defining the box (ft)
 Real Y coordinate of left end of centerline
 defining the box (ft)
 Real X coordinate of right end of centerline
 defining the box (ft).
 Real Y coordinate of right end of centerline
 defining the box (ft)
 Real Length of vertical side of the box (ft)

NOTE: Repeat proceeding data card for each box.

5. BLOCK2 is a sliding block surface generator modified from BLOCK, the difference being that BLOCK2 generates active and passive portions of the sliding blocks according to the Rankine theory, where BLOCK generates these more randomly.

INPUT FOR TIES

COMMAND CARD TIES Command Code

DATA CARD Integer Number of tieback loads
 DATA CARD Integer Boundary number where tieback load
 is applied
 Real Y coordinate of the point of application
 of tieback load (ft) or (m)
 Real Load per tieback (lbs) or (kg)
 Real Horizontal spacing between tiebacks
 (ft) or (m)
 Real Inclination of tieback load as measured
 clockwise from the horizontal plane (°)
 Real Free length of tieback (ft) or (m)
 (Equal to zero if other than a tieback load)

NOTE: Repeat preceding data card for each tieback load.

INPUT FOR SUPPRESSING OR REACTIVATING TIEBACK LOADS. (if specified)

COMMAND CARD TIES Command Code

DATA CARD Integer Number zero (0)

XII. ERROR MESSAGES

STABL is intended to be error free, assuming that the input data are correctly prepared. To avoid problems when the data have been incorrectly prepared, STABL checks all data, as they are being read in, for consistency with program requirements.

If an inconsistency is found in data submitted, STABL points it out by displaying an error indication. Unless the error is of a nature that demands immediate termination of execution, STABL continues reading data and checking for more errors until a point is reached in execution where dermination is required as a consequence of previously determined errors.

The errors are coded and referenced to descriptions in the next section. Each input error has a two digit number prefixed with two letters, associating the error with a particular command or class of errors. The prefixes are listed below.

SQ	- Command Sequence errors
FR	- Free-form Reader errors
PF	- errors associated with command PROFIL
WA	- errors associated with command WATER
SF	- errors associated with command SURFAC
LM	- errors associated with command LIMITS
LD	- errors associated with command LOADS
SL	- errors associated with command SOIL
AI	- errors associated with command ANISO
RC	- errors associated with commands RANDOM and CIRCLE
BK	- errors associated with command BLOCK
TI	- errors associated with command TIES

Command Sequence Errors

SQ01-

A command other than PROFIL has been used as the first command in the execution sequence. The first command must be PROFIL. PROFIL initializes STABL prior to reading all data pertinent to the definition of a problem. All data that would have been read prior to encountering the first use of command PROFIL would have been nullified and would not have been made available to STABL for the purpose of analyzing the first problem.

SQ02-

An attempt to compute the factor of safety of a specified trial failure surface with command EXECUT has been aborted. The isotropic soil parameters describing the soil types of the current problem do not exist. After each use of the command PROFIL in an execution sequence, the isotropic soil parameters of each soil type must be specified by use of command SOIL before command EXECUT may be used. Each time a new problem is introduced in an execution sequence by command PROFIL, the soil parameters describing soil types of preceding problems are no longer available for use.

SQ03-

An attempt to compute the factor of safety of an unspecified trial failure surface with command EXECUT has been aborted. After each use of command PROFIL, CIRCLE, RANDOM or BLOCK, a trial failure surface must be specified with command SURFACE before command EXECUT may be used.

SQ04-

The command ANISO has been used without the isotropic soil parameters being defined. Anisotropic strength data may not be specified unless the isotropic parameters have been defined by command SOIL after the last use of command PROFIL.

SQ05-

An attempt to use one of the commands, RANDOM, CIRCLE, or BLOCK has been aborted. The isotropic soil parameters describing the soil types of the current problem do not exist. After each use of command PROFIL in an execution sequence, the isotropic soil parameters of each soil type must be specified by use of command SOIL before any of the above mentioned commands may be used. Each time a new problem is introduced in an execution sequence by command PROFIL, the soil parameters describing soil types of preceding problems are no longer available for use.

Free-form Reader Error Codes

FR01-

Data are insufficient to continue execution. An attempt was made to read beyond the last data item specified. Check for missing data items or for gaps between data items on each line larger than one blank space. This error only occurs at the end of an execution sequence within the data provided with the last command used.

FR02-

The line of data displayed begins with one or more blank spaces or may be entirely blank. The first item of data of each line is required to begin in the first column. Lines entirely blank are not permitted.

FR03-

Within the line of data displayed, a decimal point has been detected for a number read as an integer. An integer is not allowed to contain a decimal point. First check if any numbers intended to be integers contain a decimal point. If not, check if error is indirectly caused by a displacement of data read. Causes of displacements are discussed below.

FR04-

Within the line of data displayed, a minus sign has been detected for a number read as an integer. All integers are required to be positive. Negative integers are never required as input for STABL. This error may be caused indirectly by displacement of data read. Causes of displacements are discussed below.

FR05-

Within the line of data displayed, an illegal character has been detected for a number read as an integer. Only numeric characters and decimal points are allowed. If a command word is displayed, the data provided with the previous command was not sufficient to complete its execution. Check for a displacement of data read. Causes of displacements are discussed below.

FR06-

Within the line of data displayed, a decimal point was not detected for a number read as a real number. A real number is required to contain a decimal point. First check if any numbers intended to be real numbers lack decimal points. If not, check if error is indirectly caused by a displacement of data read. Causes of displacements are discussed below.

FR07-

Within the line of data displayed, an illegal character has been detected for a number read as a real number. Only numeric characters, decimal point, and minus sign are allowed. If a command word is displayed, the data provided with the previous command was not sufficient to complete its execution. Check for a displacement of data read. Causes of displacements are discussed below.

Displacements of data read are caused either by inadvertently omitting items of data or by leaving gaps between items of data larger than one blank space. Data items following a gap larger than one blank space are not read. Instead, data from the next line are read in their place, producing a displacement of data read from that point on.

At some point following the displacement, an error will be produced indirectly. A real number might be read as an integer, or vice versa, producing error FR03 or FR06 respectively. A negative real number read as an integer will also produce error FR04. When a displacement occurs, and if none of the above errors are produced, the numeric data will be exhausted and finally a command word will be read as numeric data producing error FR05 or FR07 depending upon whether an integer or real number was being read. If cause of displacement is not found in the displayed line of data, check the preceding lines of data.

PROFIL Error Codes

PF01-

The number of ground surface boundaries exceeds the total number of profile boundaries. The number of profile boundaries must be less than or equal to the total number of profile boundaries.

PF02-

The number of profile boundaries specified may not exceed 100. The problem must be either redefined so fewer profile boundaries are used, or the dimensioning of the program must be increased to accommodate the problem so defined.

PF03-

A negative coordinate has been specified for the profile boundary indicated. All problem geometry must be located within the 1st quadrant.

PF04-

The coordinates of the end points of the profile boundary indicated have not been specified in the required order. The coordinates of the left end point must precede those of the right

PF05-

The ground surface boundaries indicated are not properly ordered or are not continuously connected. The ground surface boundaries must be specified from left to right and the ground surface described must be continuous.

PF06-

The required subsurface boundary order is unsatisfied for the boundaries indicated. Of boundaries which overlap horizontally, those above the others must be specified first.

WATER Error Codes

WA01-

An attempt has been made to suppress or reactivate undefined water surface data. Data must be defined by a prior use of command WATER before they can be suppressed. Suppressed data can not be reactivated if command PROFIL has been used in the execution sequence subsequent to their suppression. Command PROFIL nullifies all data prior to their use whether the data are active or suppressed.

WA02-

The number of points specified to define the water surface exceeds 40. The problem must be either redefined so fewer points are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

WA03-

Only one point has been specified to define the water surface. A minimum of two points is required.

WA04-

A negative coordinate has been specified for the water surface point indicated. All problem geometry must be located within the 1st quadrant.

WA05-

The water surface point indicates that it is not to the right of the points specified prior to it. The points defining the water surface must be specified in left to right order.

SURFAC Error Codes

SF01-

The number of points specified to define a trial failure surface exceeds 100. The problem must be either redefined so fewer points are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

SF02-

Only one point has been specified to define the trial failure surface. A minimum of two points is required.

SF03-

A negative coordinate has been specified for the trial failure surface point indicated. All problem geometry must be located within the first quadrant.

SF04-

The trial failure surface point indicated is not to the right of the points specified prior to fit. The points defining the trial failure surface must be specified in left to right order, and no two points are allowed to define a vertical line.

SF05-

The first point specified for the trial failure surface is not within the horizontal extent of the defined ground surface. All points defining a trial failure surface must be within the horizontal extent of the defined ground surface.

LIMITS Error Codes

LM01-

An attempt has been made to suppress or reactivate undefined surface generation boundary data. Data must be defined by a prior use of command LIMITS before they can be suppressed. Suppressed data can not be reactivated if command PROFIL has been used in the execution sequence subsequent to their suppression. Command PROFIL nullifies all data read prior to their use whether the data are active or suppressed.

LM02-

The number of surface generation boundaries specified to deflect upwards exceeds the total number of boundaries specified. The number of upward deflecting boundaries must not exceed the total number of boundaries.

LM03-

The number of surface generation boundaries specified exceeds 20. The problem must be either redefined so fewer surface generation boundaries are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

LM04-

A negative coordinate has been specified for the surface generation boundary indicated. All problem geometry must be located within the 1st quadrant.

LM05-

The coordinates of the end points of the surface generation boundary indicated have not been specified in the required order. The coordinates of the left end point must precede those of the right.

LOADS Error Codes

LD01-

An attempt has been made to suppress or reactivate undefined surcharge boundary loads. Data must be defined by a prior use of command LOADS before they can be suppressed. Suppressed data can not be reactivated if command PROFIL has been used in the execution sequence subsequent to their suppression. Command PROFIL nullifies all data read prior to their use, whether the data are active or suppressed.

LD02-

The number of surcharge boundary loads specified exceeds 10. The problem must be either redefined so fewer loads are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

LD03-

A negative coordinate has been specified for the surcharge boundary load indicated. All problem geometry must be located within the first quadrant.

LD04-

The X coordinates defining the horizontal extend of the surcharge boundary load indicated have not been specified in the required order. The X coordinate of the left end of the load must precede the X coordinate of the right end.

LD05-

The surcharge boundary load indicated is not to the right of all the loads specified prior to it or overlaps one or more of them. The loads must be specified left to right and are not allowed to overlap.

SOIL Error Codes**SL01-**

The profile boundary indicated with the error message has an undefined soil type index. The number of soil types specified must be greater than or equal to each soil type index which has been assigned to profile boundaries.

SL02-

The number of soil types may not exceed 20. The problem must be either redefined so fewer soil types are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

SL03-

An attempt has been made to change the parameters of one or more soil types which are undefined. No soil types have been defined since the last use of command PROFIL. When a new problem is introduced by command PROFIL, the soil parameters, describing soil types of preceding problems in the execution sequence, are no longer available for use and cannot therefore be changed.

SL04-

The number of soil types to be changed is greater than the total number of soil types already defined. This implies changing isotropic soil parameters of soil types which have not been specified and therefore is not permitted. The number of soil types to be changed must be less than or equal to the number of soil types specified by a previous use of command SOIL. Each soil type must be previously specified, before its parameters may be changed.

SL05-

An attempt has been made to change the parameters describing an unspecified soil type. The soil type must be defined before it may be modified. The index of each soil type to be changed must be less than the total number of soil types.

ANISO Error Codes

AI01-

An attempt has been made to suppress or reactivate undefined anisotropic strength data. Data must be defined by a prior use of command ANISO before they can be suppressed. Suppressed data can not be reactivated if command PROFIL has been used in the execution sequence subsequent to their suppression. Command PROFIL nullifies all data read prior to their use whether the data are active or suppressed.

AI02-

The number of anisotropic soil types specified may not exceed the number of soil types specified by command SOIL.

AI03-

The number of anisotropic soil types specified exceeds 5. The problem must be either redefined so fewer anisotropic soil types are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

AI04-

The soil type index indicated is greater than the number of soil types specified by command SOIL. The index of each anisotropic soil type must be less than or equal to the number of soil types specified.

AI05-

The number of direction ranges specified for the anisotropic soil type indicated is less than 2 or exceeds 10. No soil type should be defined anisotropic with number of direction ranges less than 2, as this means soil is isotropic. Also no soil type should exceed 10 direction ranges. If this is desired, the dimensions of the program must be increased.

AI06-

The counterclockwise limit of each direction range must be specified in counterclockwise order, if the anisotropic strength is to be properly defined for the anisotropic soil type indicated.

AI07-

The total direction range for the anisotropic soil type indicated has not been completely defined. The counterclockwise limit of the last direction range specified must be 90 degrees.

RANDOM and CIRCLE Error Codes

RC01-

The first initiation point lies to the left of the defined ground surface. The x coordinate of the first initiation point must be specified so all trial failure surfaces generated will intersect the defined ground surface when they initiate.

RC02-

The first and last initiation points are not correctly specified. They must be specified in left-right order.

RC03-

The last initiation point lies to the right of the defined ground surface. The x coordinate of the last initiation point must be specified so all trial failure surfaces generated will intersect the defined ground surface when they initiate.

RC04-

The right termination limit lies to the right of the defined ground surface. The right termination limit must be specified so all trial failure surfaces generated will intersect the defined ground surface when they terminate.

RC05-

The left and right termination limits are not correctly specified. They must be specified in left-right order.

RC06-

The last initiation point lies to the right of the right termination limit. It is impossible to successfully generate any trial failure surfaces, when the initiation point lies to the right termination limit.

RC07-

The depth limitation for trial failure surface development is negative. The depth limitation must be set at or above the x axis so the generated trial failure surfaces will not be allowed to develop below it.

RC08-

The length specified for the line segments used to generate trial failure surfaces is less than or equal to zero. The length must be greater than zero.

RC09-

An initiation point is below the depth initiation. The depth limitation must be set lower to enable the successful generation of trial failure surfaces from all initiation points.

RC10-

The number of points defining a generated trial failure surface exceeds 100. The length specified for the line segments must be increased.

RC11-

200 attempts to generate a single trial failure surface have failed. The search limitations are either too restrictive, or they actually prevent successful generation of a trial failure surface from one or more of the initiation points. Check and revise the search limitations or use an alternative trial surface generator.

RC12-

Fewer than 10 trial surfaces have been specified to be generated. A minimum of 10 must be generated.

RC13-

The angle specified as clockwise direction limit for surface generation is larger than the angle specified as counterclockwise direction limit. This is not correct. Check to see if angles have been reversed.

RC16-

The choice of using Janbu's empirical coefficient (0, 1 or 2) was incorrectly done.

RC17-

If the Janbu empirical coefficient is being used, the soil case was chosen incorrectly, i.e., not equal to one of the following integers 1, 2, 3.

BLOCK Error Codes

BK01-

The number of boxes specified for a sliding block search exceeds 10. The problem must be either redefined so fewer points are used, or the dimensioning of the program must be increased to accommodate the problem as defined.

BK02-

The length specified for the line segments used to generate the active and passive portions of the trial failure surfaces is less than or equal to zero. The length must be greater than zero.

BK03-

The two coordinate points specified to define the centerline of the box indicated have not been specified correctly. The left point must be specified first.

BK04-

The box indicated and the one specified before it are not properly ordered, or they overlap. All boxes must be specified in left to right order and the boxes are not allowed to overlap one another.

BK05-

The box indicated is wholly or partially defined outside of the 1st quadrant. All problem geometry must be located within the 1st quadrant.

BK06-

The box indicated is wholly or partially above the defined ground surface. Each box must be defined totally below the ground surface.

BK07-

It is not possible to complete the active portion of the failure surface from part of or all of the last box specified. The last box specified must be entirely to the left of the right end of the defined ground surface.

BK08-

It is not possible to complete the passive portion of the failure surface from part of or all of the first box specified. The first box specified must be entirely to the right of a fictitious line extended downward at forty-five deg with the horizontal from the left end of the defined ground surface.

BK09-

The number of points defining a generated trial failure surface exceeds 100. The length specified for the line segments of the active and passive portions of the generated trial failure surfaces must be increased.

BK10-

200 attempts to generate a single trial failure surface have failed. The search limitations are either too restrictive or they actually prevent successful generation of a trial failure surface. Check and revise the search limitations or use an alternate trial surface generator.

BK11-

Fewer than 10 trial failure surfaces have been specified to be generated. A minimum of 10 must be generated.

BK12-

The point(s) calculated on active or passive portion of the sliding block is not within the horizontal extent of the defined ground surface. Either the specified boxes should be changed or the geometry of the problem should be extended to include the point(s) in question.

BK16-

The choice of using Janbu's empirical coefficient (0, 1 or 2) was incorrectly done.

BK17-

If the Janbu empirical coefficient is being used, the soil case was chosen incorrectly, i.e., not equal to one of the following integers 1, 2, 3.

TIES Error Codes.

TI01-

An attempt has been made to suppress or reactivate undefined tieback loads. Data must be defined by a prior use of command TIES before they can be suppressed. Suppressed data can not be reactivated if command PROFIL has been used in the execution sequence subsequent to their use, whether the data are active or suppressed.

TI02-

The number of tieback loads specified exceeds 10. The problem must either be redefined so fewer tieback loads are used, or dimensioning of the program must be increased to accommodate the problem as defined.

TI03-

A negative coordinate has been specified for the tieback load indicated or the calculated Y coordinate of the end of the tieback is negative. All problem geometry must be located within the first quadrant.

TI04-

The inclination limits have been exceeded for the tieback load indicated. The inclination of a tieback load must be equal to or greater than zero deg and less than 180 deg as measured clockwise from the horizontal.

TI05-

The point of application of the tieback load specified does not lie on the ground surface boundary specified. Check the boundary number specified and the X and Y coordinates of the point of application of the tieback load indicated.

TI06-

The horizontal spacing between tiebacks for the row of tiebacks indicated is incorrect. The horizontal spacing between tiebacks must be greater than or equal to 1 ft (or 1 meter if using SI units).

TI07-

The length of the tieback indicated is incorrect. The length of a tieback must be greater than or equal to zero (ft). Zero is used for loads other than tieback type of loads.

XIII. GRAPHICAL OUTPUT

PCSTABL4M has two capacities for plotted output. The first uses plotting devices which produce high resolution plots such as Hewlett-Packard HP-7470A or HP-7475A pen plotter (Figure 19 & 20). A good representation of the problem geometry is clearly displayed. Its use provides an excellent opportunity to visually check whether data have been prepared properly. (Just because STABL accepts the data, doesn't mean they are correct). To indicate what each line segment represents, piezometric surfaces are marked with a "W" at each point defining each surface, trial surface generation limits with an "L", and surcharges with a "P", whereas soil boundaries are unmarked.

The latest version of the plotting routine, called PLOTSTBL allows a screen preview of the plotter output file. It supports both IBM Color Graphics (black and white in high resolution) and IBM Enhanced Color Graphics (up to 16 colors in high resolution) modes. The user has options to change scales, titles and see multiple plots.

PLOTSTBL, has been written in Microsoft Quickbasic, and is compiled for faster processing. It reads the plotted output file created by PCSTABL4M which contains three letter commands and coordinates for plotting

Information about hardware and software requirements, and running the PLOTSTBL appear in the next chapter.

In order to provide immediate access to basically the same plotted information, the matrix printer is used to provide crude resolution plots utilizing print characters (Figure 21). Only the end points of boundaries and series of points defining surfaces are plotted. Each point is assigned a particular character depending upon what point defines.

Having the knowledge of the problem's geometry, the user can connect the points to make the plot more recognizable. The resolution is low; characters are spaced ten per inch along the vertical axis and six per inch along the horizontal axis. As a result, more than one point may be scaled within the same plot position. When this occur, the point with the highest priority will be represented by its print character. Print characters used by STABL and the points they represent are listed below in order of priority, highest priority first.

Figure 19: Example HP-7470A plot with 100 circular surfaces.

Figure 20: Ten most critical surfaces from Figure 19

Figure 21: Example print character plot.

* end points of ground surface and subsurface profile boundaries

L end points defining surface generation boundaries

W points defining the water surface

1 points defining the most critical generated surface

2 points defining the second most critical generated surface

3 points defining the third most critical generated surface

4 points defining the fourth most critical generated surface

5 points defining the fifth most critical generated surface

6 points defining the sixth most critical generated surface

7 points defining the seventh most critical generated surface

8 points defining the eighth most critical generated surface

9 points defining the ninth most critical generated surface

0 points defining the tenth most critical generated surface

. points defining the remaining generated surface

S points defining a specified trial failure surface

T points defining location of tieback loads.

/ points defining the location of surcharge boundary loads

The locations of uniformly distributed surcharge boundary loads are represented with a combination of slashes and numerals. Load inclinations are not indicated on print character plots. The plots are intended to be viewed with the printer output rotated 90 deg counterclockwise, so the left side of each print character is faced down. Viewing a plot at this orientation, the numbers above slashes represent the left ends of a corresponding surcharge boundary loads. Likewise numbers below slashes represent the right ends of corresponding surcharge boundary loads (Figure 22).

Figure 22: Surchage Boundaries

If the extent of surcharge load is narrow, both the left and right end may appear within the same horizontal print position. The number of that surcharge boundary load then appears both above and below a single slash. Occasionally, when the surcharge boundary loads of narrow extent are located adjacent to other loads, some load numbers may be absent.

Printed character plots are also useful for checking input data, although not as conveniently as the first form mentioned. When using surface generation routines, both plots serve well as visual aids for modifying search parameters for subsequent searches.

XIV. INTRODUCTION TO PCSTABL4M

PCSTABL4M Versions

Two versions of PCSTABL4M are available for IBM compatible microcomputers.

Version 1.87 runs on any IBM compatible machine with the optional Intel 8087 Math Co-Processor. The program requires the Intel 8087 or 80287 Math Co-Processor and will not run on IBM compatible machines without it. Version 1.87 has been compiled to utilize the Math Co-Processor during execution which significantly enhances execution time.

Version 1.88 is supplied for those users who do not have the Intel 8087 Math Co-Processor. This version will run on any IBM compatible machine, however it is significantly slower than version 1.87 since it does not utilize the Intel 8087 Math Co-Processor. Version 1.88 will run in a machine with or without coprocessor, however performance on a machine with an 8087 coprocessor will be the same as that on a machine without an 8087 coprocessor.

For faster execution on machines without the 8087 math coprocessor, the 1.88 version has been compiled using an alternate math library which sacrifices a small amount of precision in return for faster execution. The amount of error is very small and is not significant for engineering purposes, however results will vary somewhat from the 1.87 version.

Version 1.87 is strongly recommended since it will run 3 to 5 times faster than version 1.88 and does not sacrifice any accuracy. For example, a moderately complex problem which generates and analyzes 100 failure surfaces using the Simplified Bishop method of slices takes approximately 4 minutes to run using the 8087 version (version 1.87), while the same problem takes approximately 12 minutes to run using the non-8087 version (version 1.88).

Running PCSTABL4M.

Hardware and Software Requirements.

The following is a list of the minimum hardware requirements for operating PCSTABL4M.

One IBM-XT or IBM compatible microcomputer with 256 kb of memory.

One double-sided, double density disk drive.

Dot matrix printer (11" or 17" wide carriage).

One 80 column monochrome display.

Optional: Hewlett-Packard 7470A two pen plotter.

Optional: One Intel 8087 Math Co-Processor.

Optional: A Color or Enhanced Color Graphics card and monitor.

PCSTABL4M will run on machines using any IBM or MS-DOS disk operating system (DOS), including DOS versions 1.0 to 3.3. Software requirements for using PCSTABL4M include:

A line editor or word processor for creating input files.

EDLIN, supplied with the DOS Operating System can be used if none is available.

Hard disk drives, other types of printers, additional memory space and the like, may enhance the efficiency of PCSTABL4M, but are not required.

Diskette Contents

PCSTABL4M is supplied on two 5 1/4 inch double-sided, double-density, floppy diskettes, and one single-sided.

double-density, floppy diskette. The contents of these diskettes are listed below:

DISK # 1

PCSTABL4M.EXE	Executable Program
EXAMPLE1.IN	Example Input Files
EXAMPLE2.IN	
EXAMPLE1.OUT	Example Output Files
EXAMPLE2.OUT	
EXAMPLE1.PLT	Example Plot Files
PLOTSTBL.EXE	Plotting Program

DISK # 2

487READ1.FOR	
487READ2.FOR	
487STABL.FOR	FORTRAN Source Code
487SURF.FOR	
487PLOT.FOR	
487MISC.FOR	

DISK # 3

487FACT.FOR	FORTRAN Source Code
487RAND.FOR	

The FORTRAN source code of PCSTABL4M has been divided into the eight files listed above. The source code is for 1.87 version (with the Math Co-Processor). These files were compiled and linked together into the executable program PCSTABL4M.EXE using the Microsoft FORTRAN compiler, version 3.2. The Microsoft compiler however is not required for running the program, and is only required if the user makes changes in the program. Note that only DISK #1 is required to run PCSTABL4M.

It is strongly recommended that the user create backup copies of the original diskettes supplied, and use these copies for day-to-day use, while saving the original diskettes for permanent storage.

Creation of Input Files

Input files for PCSTABL4M utilize free-format data entry, as used by other versions of STABL. Input files may be created using a line editor, text editor, or a word processor. Since word processors generally store format characters along with the text, input files must be saved without formatting so that format characters will not be encountered when running the program. If such characters are encountered, execution errors will result.

Refer to preceding pages for proper formatting of input data.

Running PCSTABL4M

Operation of PCSTABL4M is very simple. After creating an input file and storing it on a diskette, simply type "PCSTABL4M" in either uppercase or lowercase letters followed by a return. The program will be loaded into memory and will prompt the user for the current date, time, name of the user, input filename, output filename, and filename for subsequent plotting of output. The date, time, and name of the user may be in any form desired. Note that the input and output files do not need to be on the same diskette or disk drive with PCSTABL4M, as supplied on disk #1. Disk drive specifications may be used when invoking PCSTABL4M (i.e., B:PCSTABL4M), or when specifying input and output files (i.e., A:EXAMPLE1.OUT). In addition, if an invalid or nonexistent input filename is specified, the operating system will display an error message to the screen and return the user to the DOS prompt.

Filenames for the output file and the plotted output file may be any legal DOS filename. Note that an existing output file on a diskette will be overwritten if an existing output filename is reused. To avoid overwriting existing files, use unique names for each output. All responses to prompts may be uppercase or lowercase characters, including numbers and legal DOS filename symbols.

The program will write the output to the screen and the disk simultaneously. This includes the input parameters, method of analysis, and results. When running a problem which analyzes many surfaces, no output will be written to the screen while trial surfaces are being generated and analyzed. After all surfaces have been generated and analyzed, and the ten most critical factors of safety

sorted, the program will resume displaying the results to the screen.

If a plotted output file is specified, the program will write commands and sets of coordinates to the disk for subsequent plotting by the PLOTSTBL program on a Hewlett-Packard plotter. If a plotted output file is not desired, simply type "None" when prompted for the plotted output filename. To save diskette space, only specify a plotted output file for those runs whose outputs will be plotted using PLOTSTBL. Note that plotting is not performed during execution of PCSTABL4M. This allows the user to examine the results, and plot those only results which are desired.

Plotting Routine for PCSTABL4M
(PLOTSTBL)

Hardware and Software Requirements.

The only hardware required for plotting graphical output is a Hewlett-Packard HP-7470A or HP-7475A pen plotter.

PLOTSTBL is written such that the plotter must be configured at a baud rate of 9600 and connected to serial communication port #1 on the microcomputer. For further information on interfacing an HP plotter with the user's specific microcomputer, the user should consult his or her own plotter and microcomputer manuals.

Running PLOTSTBL

Type "PLOTSTBL". The program will prompt the user for the name of the input file to be used for plotting, the first line of the plot title and the second line of the plot title. The next step is the selection of the screen mode. The user can select between the color graphics adapter and the enhanced color adapter with a color or with a monochrome monitor. The program then automatically scales the image, and asks the user whether he wants to change it. The plots are then created on screen. The user can switch between plots by pressing the "enter" key. After the last plot is generated, the user can get a list of options by pressing the "/" key. The options include quitting the program, plotting another file, change the title or the scale or dumping the screen to a plotter, in which case there is a request for pen changes, and units for labeling the plot. If pen changes are specified, the program will ask the user if a two or six pen plotter is being used. As with PCSTABL4M,

disk drive specifications may be used when invoking PLOTSTBL or specifying the input file. The file to be used for plotting must be an existing file on a hard disk or diskette. If the input file specified for plotting is nonexistent, the program will display an error message. The title of the plot may contain uppercase and lowercase letters, numbers and symbols, and will appear at the top of the plot.

The user may enhance the plot by specifying that the program prompt the user for pen changes during plotting. This allows the user various colors and pen thicknesses during plotting. PLOTSTBL is written so that the user may use any number of pens during plotting and the user is not restricted to the number of pens available on the plotter being used. The program will stop during execution, return the pen to its holder, and prompt the user for a pen change for a particular set of line segments (i.e., boundaries, water surfaces, etc.). The user then specifies the desired pen, and if necessary, replaces the desired pen in the user specified pen holder, and the program continues plotting. The user may also specify that no pen changes are desired. In this case, only pen #1 will be used for the entire plot.

For convenience, an option for specifying the units of the plot is provided. The user may specify that the plot be labeled in either "Feet" or "Meters". Note that specifying either unit does not alter the plot, only the label on the axes of the plot.

For outputs where more than ten surfaces have been generated, two plots will be produced. The first plot will contain all the surfaces generated, while the second plot will contain either the ten or the first most critical surfaces. The user will be prompted to change the paper and place the desired pen for the axes of the plot in pen holder #1. The most critical failure surface plotted will be noted by asterisks (*).

REFERENCES

- Boutrup, Eva 1977, "Computerized Slope Stability Analysis for Indiana Highways", Joint Highway Research Project No. 77-25 and 77-26 (volumes), School of Civil Engineering, Purdue University, W. Lafayette, Indiana, Dec., 512 pp.
- Boutrup, E. and Lovell, C. W. (1978), "Searching Techniques in Slope Stability Analysis" (Extended Abstract). Proceedings, 15th Annual Meeting of the Society of Engineering of Engineering Science, Gainesville, Florida. Dec., pp. 447-452.
- Boutrup, E., Lovell, C. W. and Siegel, R. A. (1979), "STABL2....A Computer Program for General Slope Stability Analysis", Proceedings, 3rd International Conference on Numerical Methods in Geomechanics, Aachen, W. Germany, pp. 747-757
- Boutrup, E. and Lovell, C. W. (1980), "Searching Techniques in Slope Stability Analysis", Engineering Geology, Vol. 16, No. 1/2, July. Special Issue on Mechanics of Landslide and Slope Stability, pp. 51-61.
- Carter, R. K. (1971), "Computer Oriented Slope Stability Analysis by Method of Slices", Thesis, MSCE Purdue University, West Lafayette, Indiana, Jan., 120 pp.
pr
- Chen, R-H (1981), "Three-Dimensional Slope Stability Analysis", Joint Highway Research Project No. 81-17, School of Civil Engineering, Purdue University, West Lafayette, Indiana, Dec., 298 pp.
- Lovell, C. W. (1982) "Three-Dimensional Slope Stability", Thirteenth Annual Ohio River Valley Soils Seminar, Lexington, Kentucky, Oct., 9 pp.
- Rooney, M. F., Howland, J. D. and Molz, R. J. (1982), "Implementing Large Programs on Microcomputers", Journal, Technical Councils of ASCE, Vol. 108, No. TCI, May, pp. 125-137.

Siegel, R. A. (1975a), "Computer Analysis of General Slope Stability Problems", Joint Highway Research Project No. 75-8, School of Civil Engineering, Purdue University, West Lafayette, Indiana, May, 210 pp.

Siegel, R. A. (1975b), "STABL User Manual", Joint Highway Research Project No. 75-9, School of Civil Engineering, Purdue University, West Lafayette, Indiana, May, 104 pp. (Revised by E. Boutrup, June 1978).

Siegel, R. A., Kovacs, W. D. and Lovell, C. W. (1978), "New Method for Shear Surface Generation for Stability Analysis", Proceedings, 29th Annual Highway Geology Symposium, Annapolis, Maryland, May, pp. 295-312.

Siegel, R. A., Kovacs, W. D. and Lovell, C. W. (1981), "Random Surface Generation in Stability Analysis", Journal, Geotechnical Engineering Division, ASCE, July, pp. 998-1002.

Taylor, D.W. (1948), "Fundamentals of Soil Mechanics", Wiley & Sons, New York, pp. 455-462.

Tenier, P. and Morlier, P. (1982), "Influence of Concentrated Loads on Slope Stability", Canadian Geotechnical Journal, Vol. 19, Feb., pp. 396-400.

Appendix 1 - Latest Implementations of PCSTABL4M Janbu's Correction Factor

One of the methods of analysis in PCSTABL4M is Janbu's Simplified Method of Slices. The method has gained popularity mainly because of its simplicity and computational speed. It differs from Janbu's original generalized method of slices (1954, 1957) in that it neglects the interslice forces. Janbu has compared his two methods for different combinations of soil strength parameters, slope inclinations and failure surface positions, and proposed a correction factor f_0 (Figure A1) which is to be applied to the usually conservative simplified version. The former versions of PCSTABL did not incorporate this correction factor, what could lead to conservativisms of up to 13% for deep surfaces in cohesive soils.

In PCSTABL4M this correction factor is automatically calculated based on the set of three equations, presented by Hoek and Bray (1974):

$$f_0 = 1.0 + K [(d/l) - 1.4(d/l)^2]$$

Where the value of K depends on the strength properties of the soil:

- a) for $\phi = 0$, $K = 0.69$
- b) for $c > 0$ and $\phi > 0$, $K = 0.5$
- c) for $c = 0$, $K = 0.31$

These equations reproduce the curves on Figure A1, where the parameters "l" and "d" are also defined. All the routines in PCSTABL4M that make use of Janbu's Simplified method (SURFAC, CIRCLE, RANDOM and BLOCK) have been modified to incorporate the correction factor, and the new input format for these routines have been described in chapter XI. The program lets the user decide whether to use the correction factor or not, for comparison purposes. The user can also select which strength parameter case is pertinent to the slope. For homogeneous slopes, this should pose no problem, but for layered slopes, the selection can sometimes be difficult. It has been suggested that since the correction factor is a multiplicative factor inside a summation, it could be applied to each slice according to its material. The problem with this procedure is that it contradicts the way the correction curves have been developed and thus it does not guarantee that the iterating process would converge to the correct factor of safety. If the slope material is too heterogeneous to allow the use of one of the above

Figure A1: Janbu's Correction Factor

curves, a more general method, as the method of Spencer (available in PCSTABL5M) should be used.

It is very important to realize that the use of a correction factor does not bring simplified methods to the category of general methods. At best, it makes both approaches give closer factors of safety, but only under conditions for which the correction factors have been developed. The non incorporation of interslice forces by Janbu's Simplified Method can make it give conservative factors of safety when high, non uniform porepressures are present in the slope, and the use the correction factor will not compensate for this condition. Thus it must be kept in mind by the engineer at all times that although Janbu's Simplified Method is a flexible, fast and widespread method of analysis, it is an approximate method and should not substitute for more accurate methods in face of complex and/or critical conditions.

Pore Pressures

PCSTABL4M, as its predecessors, allows the user to define porepressure conditions by using phreatic lines or the so called porepressure ratio R_u . The first of these approaches is often confused with piezometric lines concept, what is unfortunate. A phreatic line can not be used accurately to describe the porepressures in the soil beneath it without the appropriate estimate of the associated equipotentials. And for one single phreatic line, each different failure surface analyzed has its own piezometric line. Since an accurate estimate of such equipotentials for general situations can only be performed by finite differences or similar methods, the former versions of STABL used a conservative approach of calculating the pore pressure at the bases of slices, based on hydrostatic pressure. That means that the vertical distance from the base of the slice to the phreatic line immediately above was taken as the water head. This procedure can give heads as much as 33% higher than actual heads, when the phreatic surface is dipping at 35°.

It has been proposed an approximate method where the equipotential passing trough the base of the slice would be approximated by a straight line normal to the tangent to the phreatic line at the top of the slice (Figure A2). This method nevertheless, is valid only when the phreatic line tangent is constant (as in an infinite slope problem), and can produce non conservative pore pressures in real

Figure A2: Pore Pressures

situations. In Figure A3, a plot of the derivative of the tangent to a usual phreatic line is shown, and at the point where the derivative is maximum, (tangent angle = 35°) the method gives porepressures up to 11% lower than the actual ones. This difference reduces as the derivative approaches zero.

In order to preserve the confiability of the analysis, it was decided that the average of the two methods would avoid excessive conservatisms, while preventing nonconservative estimates of the porepressures, that would result from the "perpendicular approach". As can be seen in Figure A3, for a 35° phreatic line, the overestimation of the pressure head decreased from about 33% with the old method to approximately 9% with the averaged model.

For illustration purposes, a slope was analyzed with four different phreatic conditions, using the three different methods. The geometry can be seen in Figure A4 and the results are displayed in Table A1. As it can be noticed, PCSTABL4 is the most conservative, while the perpendicular method produced the highest factors of safety. The average method produced factors of safety in between both methods. All three methods are available in PCSTABL4M.

Table A1 - Comparison Between The Three Approaches for Pore Pressure Determination

PHREATIC LINE	METHOD	MINIMUM SAFETY FACTOR
IA	PCSTABL4 (Old)	0.817
	Perpendicular	0.817
	Average	0.817
IB	PCSTABL4 (Old)	0.688
	Perpendicular	0.703
	Average	0.695
IC	PCSTABL4 (Old)	0.585
	Perpendicular	0.615
	Average	0.600
ID	PCSTABL4 (Old)	0.555
	Perpendicular	0.586
	Average	0.571

Figure A3: Different Approaches

Figure A4: Phreatic Conditions

Algorithm Modifications and Error Corrections

Modification of the Routine SURBIS:

The routine SURBIS evaluates the factor of safety of user defined surfaces using simplified Bishop's method. This method was developed to be used with circular surfaces, and the program thus assumes that the points used to define the surface follow a circular pattern. In the former program PCSTABL4, the three first points of the defined surface were used to calculate the center about which the moment equilibrium should be performed (as well as the circle's radius). This procedure was found to be the source of inaccuracies for the following reasons:

a) The first three points are usually very close and represent a very small portion of the surface. Consequently scale effects would increase the influence of any minor misalignment on the calculation of the center.

b) This fitting method is very sensitive to slight variations of accuracy in the coordinates of the points, including rounding of decimals.

The new program PCSTABL4M uses the first, the last and the middle points to calculate the center of rotation. This modification virtually eliminates the former problems. Besides, it better represents the way data is entered for back analysis of real situations, where the engineer usually has certainty about the initial and final points of the failure surface as well as some data measured from the middle section of the slide.

Influence of Number of Points on the Calculated Center Position

In order to show how this modification affects the results, a unique circular failure surface, defined by three different number of points (8, 11 and 18 points) had its center of moments calculated. The points coordinates were estimated graphically, as in normal design situation. The surface was analyzed for a fixed slope geometry (Figure A5). Table A2 shows how the new routine in PCSTABL4M improved the consistency of the calculated centers and radius over PCSTABL4.

Figure A5: Test Profile

The circles fit by the older and newer versions of STABL are shown in Figure A6. It is obvious that although there is good agreement in the region of the first three points of the surface, the centers of rotation calculated by the older version are completely different and inconsistent analysis is expected.

TABLE A2: Consistency of Centers and Radius.

PROGR.	#POINTS	CENTER	RADIUS
PCSTABL4	8	15.0,34.9	32.5
PCSTABL4	11	15.4,30.6	28.5
PCSTABL4	18	-34.2,-155.	163.7
PCSTABL4M	8	15.2,30.9	28.8
PCSTABL4M	11	15.4,30.6	28.8
PCSTABL4M	18	15.3,30.7	28.7

Slice Data Output and Other Modifications

The program PCSTABL4M has undergone some other minor modifications which are listed below:

a) The program now prints slice data for the most critical surface as part of the standard output, including thickness, weight, water forces on top and bottom of the slice, normal tieback force, tangential tieback force, boundary external loads, horizontal and vertical earthquake forces.

b) The code has been corrected so that a division by zero resulting from the occasional generation of very thin slices does not occur anymore.

Figure A6: Surface Fitting

Appendix 2 - Comparative Study

The new features implemented in the program PCSTABL4M act simultaneously. Thus comparisons with other programs where similar features are not present may not be totally meaningful. A number of programs (ICES, PCSTABL4, TSTAB) and different methods of analysis (Spencer, Janbu, Bishop, Sarma) were used in this comparison, but emphasis was given in comparing PCSTABL4 and the new PCSTABL4M. The parametric analyses show the engineer the overall performance of the new program under a range of situations. The following problems attempt to identify cases where the engineer will profit most from PCSTABL4M new features.

The initial 16 analyses covered the new porepressure approach as well as the correction factors now present in Janbu's analysis. The problems have a simple geometry and represent a rapid drawdown condition, with four different phreatic line levels. For each phreatic line, 3 soils with different strength parameters were used - a cohesive soil ($c'=300$ psf), a soil with both cohesion and shear resistance ($c'=150$ psf, $\phi'=20^\circ$), and a cohesionless soil ($\phi'=30^\circ$). Since the literature says that Janbu's correction factors work best with low-angle slopes, the slope was kept constant at 1:1, a steep inclination, for the 16 cases. This should determine how the program performed under the least favorable conditions. Results were hand checked for both PCSTABL4M and the old version PCSTABL4. PCSTABL4M was run using the average porepressure model with all problems.

The geometry of the problems are shown in Figure A7. The lines a,b,c and d represent the phreatic line, changing position with time, after a rapid drawdown. In practical situations, Janbu's method should be used only with non-circular surfaces, but since the slope is homogeneous, Janbu's method was run with circular surfaces and compared with Simplified Bishop's. The results are presented in Table A3, where soil 1 is the cohesionless soil, soil 2 has both cohesion and shear strength and soil 3 is purely cohesive. Since no other program available used the sloping porepressure approach, hand calculated factors of safety for the critical surfaces (Figure A8) using Bishop's Method are presented for comparison. In these hand calculations, porepressures were estimated from flow nets. The agreement is quite good, with PCSTABL4M being no more than 8% conservative, as expected. The old version calculated factors of safety as much as 33% conservative. Another important accomplishment is the fact that the use of either Janbu's or Bishop's methods now result in very similar factors of safety. Table A4 displays the absolute values of the differences (in %) between the factors of safety

Figure A7: Problems Geometry

TABLE A3

MIN. FACTORS OF SAFETY

LINE A

PROGR.	METHOD	SOIL 1	SOIL2	SOIL3
STABL4	BISHOP	0.572	0.817	0.483
STABL4	JANBU	0.569	0.766	0.479
STABL4M	BISHOP	0.572	0.817	0.483
STABL4M	JANBU	0.574	0.806	0.515
HAND CALCUL.	BISHOP	0.573	0.819	0.483

LINE B

PROGR.	METHOD	SOIL 1	SOIL2	SOIL3
STABL4	BISHOP	0.136	0.380	0.308
STABL4	JANBU	0.173	0.356	0.316
STABL4M	BISHOP	0.203	0.444	0.309
STABL4M	JANBU	0.201	0.437	0.315
HAND CALCUL.	BISHOP	0.211	0.460	0.312

LINE C

PROGR.	METHOD	SOIL 1	SOIL2	SOIL3
STABL4	BISHOP	0.258	0.442	0.309
STABL4	JANBU	0.263	0.417	0.317
STABL4M	BISHOP	0.334	0.487	0.310
STABL4M	JANBU	0.340	0.486	0.329
HAND CALCUL.	BISHOP	0.337	0.490	0.319

LINE D

PROGR.	METHOD	SOIL 1	SOIL2	SOIL3
STABL4	BISHOP	0.429	0.514	0.310
STABL4	JANBU	0.405	0.485	0.318
STABL4M	BISHOP	0.467	0.544	0.311
STABL4M	JANBU	0.470	0.545	0.329
HAND CALCUL.	BISHOP	0.466	0.543	0.319

TABLE A4 ABSOLUTE VAL. DIFFERENCE
BETWEEN JANBU's AND
BISHOPS METHODS (%)

LINE A

PROGR.	SOIL 1	SOIL2	SOIL3
STABL4	0.5%	6.2%	0.8%
STABL4M	0.3%	1.3%	6.6%

LINE B

PROGR.	SOIL 1	SOIL2	SOIL3
STABL4	27.%	6.3%	2.6%
STABL4M	1.0%	1.6%	1.9%

LINE C

PROGR.	SOIL 1	SOIL2	SOIL3
STABL4	1.9%	5.7%	2.6%
STABL4M	1.8%	0.2%	6.1%

LINE D

PROGR.	SOIL 1	SOIL2	SOIL3
STABL4	5.6%	5.6%	2.6%
STABL4M	0.6%	0.2%	5.8%

Figure A8: Critical Surfaces

calculated by the two methods. in the old and in the new programs.

As it has been widely discussed in the literature, Janbu's correction factors are not very useful for deep failure surfaces. This seemed to be confirmed by the results on the third soil column (cohesive soil) on Table A4. For these soils deep failure surfaces are critical and the difference between Bishop's method and the corrected Janbu's method seemed to increase over the non corrected method. Nevertheless, for soils with shear strength, the correction factor virtually eliminated the difference (average now is of only 1%) between both methods. When analyzing deep surfaces, the user has still the option of using the non-corrected Janbu's method. As for how each method compares with its old version, Table A5 shows the differences in the factors of safety calculated by the same methods in the new and the old versions of PCSTABL. The largest differences happened in cohesionless soils, where the old version was up to 33% conservative.

Another study performed was to test how the correction factor would perform under different slope inclinations. The correction factor was originally developed for low inclination slopes, and it was necessary to see whether it would perform poorly in steep slopes. To isolate the variable inclination, the geometry (Figure A9) consisted of a homogeneous, dry slope, with angles ranging from 5° to 45° . The three sets of soil strength parameters from the former study were used again.

The resulting minimum factors of safety are displayed in Table A6, for both Bishop's and Janbu's method. For comparison purposes, IGES' and TSTAB's Bishop's minimum factors of safety and hand calculated checks are also provided.

The analyses showed that the new corrected Janbu's method compared consistently with Bishop's method for all slope inclinations, as far as the soil was not purely cohesive. Soils with shear strength did not show any particular trend to have the two methods differ more with steeper slopes. Nevertheless, this trend was identified for the third soil, where the friction angle is zero.

TABLE A5 ABSOLUTE VAL. DIFFERENCE
 BETWEEN SAME METHODS
 IN PCSTABL4M AND PCSTABL4 (%)

LINE A

METHOD	SOIL 1	SOIL2	SOIL3
BISHOP	0.0%	0.0%	0.3%
JANBU	1.2%	5.0%	3.3%

LINE B

METHOD	SOIL 1	SOIL2	SOIL3
BISHOP	33%	14.4%	0.3%
JANBU	13.9%	18.5%	3.6%

LINE C

METHOD	SOIL 1	SOIL2	SOIL3
BISHOP	23%	9.2%	0.3%
JANBU	22.6%	14 %	0.3%

LINE D

PROGR.	SOIL 1	SOIL2	SOIL3
BISHOP	8.0%	5.5%	0.0%
JANBU	13.8%	11 %	7.0%

TABLE A6 EFFECT OF SLOPE INCLINATION
ON THE ACCURACY
OF JANBU'S METHOD

SLOPE	SOIL 1 BISHOP JANBU		SOIL 2 BISHOP JANBU		SOIL 3 BISHOP JANBU	
A) 7°	4.624	4.638	6.052	6.151	2.027	2.122
Diff (%)	0.3%		1.6%		4.7%	
IGES	4.625		6.076		2.109	
TSTAB	4.626		6.115		2.058	
Hand-Calc.	4.603		6.101		2.000	
B) 20°	1.542	1.548	1.612	1.625	0.582	0.801
Diff (%)	0.4%		0.8%		3.3%	
IGES	1.560		1.623		0.595	
TSTAB	1.557		1.635		0.576	
Hand-Calc.	1.540		1.607		0.588	
C) 36°	0.774	0.777	0.829	0.829	0.254	0.284
Diff (%)	0.4%		0 %		11%	
IGES	0.782		0.823		0.267	
TSTAB	0.780		0.835		0.249	
Hand-Calc.	0.770		0.807		0.260	
D) 45°	0.590	0.591	0.677	0.649	0.185	0.216
Diff. (%)	0.2%		4 %		16%	
IGES	0.596		0.663		0.189	
TSTAB	0.594		0.685		0.195	
Hand-Calc.	0.589		0.681		0.182	

Comments About The Choice of Parameters For Use in STABL

Once the effects of the new features of STABL4M on the factors of safety have been studied, the next step will be to review the concepts involved in using PCSTABL4M on regular analyses. The most common problems faced by users take place at the time they define the search parameters. Many times, conflicting combinations of such parameters are a mere result of user attempts to perform in one single step a search that should be broken in several steps. In other words, users often try to create search boundaries so general that the program is faced with inconsistent conditions. Some guidelines on how to avoid inconsistencies are listed in the following paragraphs.

When a circular surface searching procedure is specified, most of the problems during runtime are caused by inappropriate combinations of the one or more of the following parameters:

- a) length of segments defining surface
- b) clockwise and counterclockwise initiation angle limits
- c) "X" leftmost and rightmost initiation and/or termination points.

The following checks should be followed to assure proper parameter selection:

a) When defining the initiation and termination intervals, do not overlap the rightmost initiation point and the leftmost termination point.

b) When defining the length of the segments forming the surface, make sure that the length is such that if the first segment's angle was the counterclockwise angle limit, it would not end above the ground. This can happen when surfaces are being initiated close to the top of a slope.

c) When defining the initiation angle limits, remember that the counterclockwise angle should not let the first segment of a surface being generated go above the ground. This means that it should be smaller or equal to the minimum ground slope inside the initiation region.

Another problem frequently happens when using the block search option. It occurs when the user places the extreme boxes in positions where active or passive wedges starting from these boxes would fall outside the bounds of the geometry. To avoid this problem the user should estimate the passive and active lines passing through the leftmost point of the initiation region and the rightmost point of the

termination region respectively, and make sure that the boxes are inside the zone defined by these two lines.

Some users have attempted to perform general sensitivity studies about how the number and size of boxes or the number of surfaces generated affect the search and/or the minimum factor of safety. Unfortunately, there are no such general correlations.

Each slope being evaluated has an initially unknown failure surface which has the minimum factor of safety possible. The program evaluates surfaces generated randomly within a user specified region of that slope. The generation of random surfaces can be seen as a Monte Carlo simulation process and the number of generated surfaces necessary to find the minimum factor of safety depends on how close to the originally unknown critical surface the search region was specified.

In the same way, the optimum number of boxes is case specific. For instance, if a user tried to find the most critical surface in an homogeneous slope, where the critical surface is close to circular, a large number of boxes would be necessary, since the curvature of the surface would have to be accommodated. On the other hand, in a slope where the failure surface is bound to pass within a very thin and linearly inclined layer, a large number of boxes will bring no consistent improvement to the analyses whatsoever.

The influence of the size of the boxes on the number of surfaces necessary to reach the minimum factor of safety is also dependent on how close their positions are with respect to the unknown most critical surface. The larger the boxes, the larger the number of surfaces necessary to cover thoroughly the region defined. Consequently large boxes should be used only when the user is trying to locate the most critical region of the slope. After the region has been located, the size of the boxes should be reduced to concentrate the surfaces being generated in the important zone and avoid waste of computational effort.

In other words, small boxes placed far from the actual critical surface would never let the program find the minimum factor of safety, no matter how many trial surfaces were generated. On the other hand, if boxes as small as points were placed by coincidence right on the top of the critical surface, we would have an optimum search (when only one surface would need to be generated), and increasing their sizes would bring no benefit to the search.

Another aspect relevant to the analysis, is the number of slices used during the factor of safety calculations. Figure A10 displays the typical expected variance of the factor of

FIGURE A10: Influence of Number of Slices

safety as a function of the used number of slices. These results were obtained as an average from many cases with different slopes and soils. There seemed to be no particular trend that would justify separating the influence for different soil-profile combinations. Consequently, in general, the factor of safety obtained with a smaller number of slices will be more conservative. Since a larger number of slices results in longer calculation times, the user is advised to perform a search with a segment length that results in about 15 to 20 slices. This would keep the factors of safety only about 2% conservative and the search would not suffer speed decay. The most critical surface can latter be individually analyzed with a smaller segment length so that the accuracy can be increased.

Appendix 3 - Examples

The input files for the examples presented here are supplied on the standard distribution diskette for PCSTABL4M, as are their resulting output files. Each example follows a similar format. First, there is a short description of the problem, including a figure showing the geometry. The engineering properties of the soils are included as supplied data. Following there is a listing of the input data set and the sample terminal session showing exactly what the user should respond when prompted by the terminal during execution of PCSTABL4M. Finally, there is a listing of the output file and the plottings.

Example 1

This example concerns the long term stability of a cut in soft clay material. The slope is composed of one soil type, but is defined by two types in the problem. Soil type two is in tension and thus is assigned zero shear strength. Bedrock is defined and considered a limit for the failure surface. The circular failure surface searching option was chosen. Limits were set to confine the failure surface generation within the area of expected failure. The limits were determined after a previous, more general run found the ten most critical surfaces to occur within these limits. This example is a final run to check the possibility that the critical surface passes through the toe.

Twenty five surfaces are generated from each of 3 initiation points; the leftmost at the toe, the rightmost as $x = 50\text{ft}$. If a circular surface through the toe is critical, then most of the critical surfaces subsequently determined should pass through the toe. All surfaces to be generated will lie within a zone somewhat matching that of the ten most critical surfaces of the previous run.

Figure A11 shows the problem geometry. The input file is described bellow. The comments in parentheses are not part of the file, but comments included to help the user understand the structure of the file.

Figure A11: Example 1 Geometry

Input File:

```

PROFIL                                     (Initialization)
PCSTABL4M Example #1                     (title)
6 5
0. 68. 22. 67. 1
22. 67. 38. 63. 1
38. 63. 101. 88. 1
101. 88. 138. 103. 2
138. 103. 205. 110. 2
101. 88. 205. 99. 1
SOIL                                     (Soil parameter
2                                     definition)
116.4 124.2 500. 14. 0. 0. 1
116.4 116.4 0. 0. 0. 0. 1
WATER                                     (Piezometric Line definition)
1 3 0.                                   (#3 ->Average Porepressure Model selected)
9
0. 68.
22. 67.
38. 63.
63. 73.
83. 78.
104. 82.
122. 85.
140. 87.
205. 93.
LIMITS                                   (Searching Boundaries Limits)
10 8
0. 15. 29. 24.
29. 24. 51. 26.
51. 26. 78. 56.
78. 56. 94. 65.
94. 65. 113. 64.
113. 64. 133. 56.
133. 56. 161. 58.
161. 58. 205. 76.
63. 73. 93. 67.
93. 67. 138. 103.
CIRCLE                                   (Circular Search using Modified
1                                   Janbu's Method - with automatic
2                                   correction factor ...)
25
38. 50. 138. 170.
0. 10. 0. -25.

```

The above file is created using a word processor and stored in the disk. The user will be required to supply the name of the file as shown in the sample terminal session bellow:

A>
A>pcstabl4m

**** PCSTABL4M ****

Slope Stability Program
by
Purdue University

(user answers)

Date..... 7/1/88
Time of Run..... 5:25 pm
Your Name or Initials..... Thomaz
Input Data Filename..... ex1.in
Output Filename..... ex1.out
Plotted Output Filename
(Enter "None" if not desired).... ex1.plt

.
.
.

After which the program starts running. The output file generated, ex1.out, can be seen bellow.

**** PCSTABL4M ****

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date:
Time of Run:
Run By:
Input Data Filename: ex1.in
Output Filename: ex1.out
Plotted Output Filename: ex1.plt

PROBLEM DESCRIPTION PCSTABL4M Example #1

BOUNDARY COORDINATES

5 Top Boundaries
6 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below Bnd
1	.00	68.00	22.00	67.00	1
2	22.00	67.00	38.00	63.00	1
3	38.00	63.00	101.00	88.00	1
4	101.00	88.00	138.00	103.00	2
5	138.00	103.00	205.00	110.00	2
6	101.00	88.00	205.00	99.00	1

ISOTROPIC SOIL PARAMETERS

2 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	116.4	124.2	500.0	14.0	.00	.0	1
2	116.4	116.4	.0	.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

THE POREPRESSURE MODEL CHOSEN IS:

Average of Hydrostatic/Perpendicular

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 9 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	68.00
2	22.00	67.00
3	38.00	63.00
4	63.00	73.00
5	83.00	78.00
6	104.00	82.00
7	122.00	85.00
8	140.00	87.00
9	205.00	93.00

Searching Routine Will Be Limited To An Area Defined By 10 Boundaries
Of Which The First 8 Boundaries Will Deflect Surfaces Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	15.00	29.00	24.00
2	29.00	24.00	51.00	26.00
3	51.00	26.00	78.00	56.00
4	78.00	56.00	94.00	65.00
5	94.00	65.00	113.00	64.00
6	113.00	64.00	133.00	56.00
7	133.00	56.00	161.00	58.00
8	161.00	58.00	205.00	76.00
9	63.00	73.00	93.00	67.00
10	93.00	67.00	138.00	103.00

A Critical Failure Surface Searching Method, Using A Random Technique For Generating Circular Surfaces, Has Been Specified.

Janbu's Empirical Coef. is being used for
both cohesion and shear angle greater than 0
75 Trial Surfaces Have Been Generated.

25 Surfaces Initiate From Each Of 3 Points Equally Spaced
Along The Ground Surface Between X = 38.00 ft.
and X = 50.00 ft.

Each Surface Terminates Between X = 138.00 ft.
and X = 170.00 ft.

Unless Further Limitations Were Imposed, The Minimum Elevation
At Which A Surface Extends Is Y = .00 ft.

10.00 ft. Line Segments Define Each Trial Failure Surface.

Restrictions Have Been Imposed Upon The Angle Of Initiation.
The Angle Has Been Restricted Between The Angles Of -25.0
And .0 deg.

Following Are Displayed The Ten Most Critical Of The Trial
Failure Surfaces Examined. They Are Ordered - Most Critical
First.

* * Safety Factors Are Calculated By The Modified Janbu Method * *

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.79	60.95
3	57.74	59.93
4	67.74	59.93
5	77.68	60.96
6	87.47	63.00
7	97.00	66.04
8	106.16	70.05
9	114.86	74.97
10	123.01	80.77
11	130.52	87.37
12	137.32	94.71
13	143.32	102.71
14	143.86	103.61

*** 1.342 ***

Individual data on the 21 slices

Slice No.	Width Ft(m)	Weight Lbs(kg)	Water	Water	Tie	Tie	Earthquake		
			Force Top	Force Bot	Force Norm	Force Tan	Force Hor	Force Ver	Surcharge Load
			Lbs(kg)	Lbs(kg)	Lbs(kg)	Lbs(kg)	Lbs(kg)	Lbs(kg)	Lbs(kg)
1	9.8	3590.0	.0	1731.5	.0	.0	.0	.0	.0
2	9.9	10357.2	.0	4917.4	.0	.0	.0	.0	.0
3	5.3	7780.9	.0	3675.9	.0	.0	.0	.0	.0
4	4.7	8171.1	.0	3919.6	.0	.0	.0	.0	.0
5	9.9	20038.2	.0	9076.1	.0	.0	.0	.0	.0
6	5.3	11956.8	.0	5205.7	.0	.0	.0	.0	.0
7	4.5	10543.0	.0	4450.6	.0	.0	.0	.0	.0
8	9.5	23288.0	.0	9341.0	.0	.0	.0	.0	.0
9	4.0	9884.7	.0	3783.6	.0	.0	.0	.0	.0
10	3.0	7344.6	.0	2662.7	.0	.0	.0	.0	.0
11	2.2	5258.9	.0	1829.4	.0	.0	.0	.0	.0
12	8.7	20303.2	.0	6508.7	.0	.0	.0	.0	.0
13	7.1	14961.8	.0	3715.8	.0	.0	.0	.0	.0
14	1.0	1959.4	.0	358.2	.0	.0	.0	.0	.0
15	5.7	9847.5	.0	1014.0	.0	.0	.0	.0	.0
16	1.9	2815.6	.0	.0	.0	.0	.0	.0	.0

17	3.8	5060.0	.0	.0	.0	.0	.0	.0	.0
18	2.9	3085.4	.0	.0	.0	.0	.0	.0	.0
19	.7	612.9	.0	.0	.0	.0	.0	.0	.0
20	5.3	2544.1	.0	.0	.0	.0	.0	.0	.0
21	.5	26.6	.0	.0	.0	.0	.0	.0	.0

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.82	61.12
3	57.78	60.20
4	67.78	60.26
5	77.73	61.29
6	87.53	63.28
7	97.08	66.22
8	106.31	70.08
9	115.12	74.81
10	123.43	80.38
11	131.15	86.73
12	138.22	93.80
13	144.57	101.53
14	146.13	103.85

*** 1.343 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.75	60.79
3	57.69	59.66
4	67.69	59.63
5	77.63	60.70
6	87.40	62.85
7	96.87	66.07
8	105.92	70.31
9	114.46	75.51
10	122.38	81.62
11	129.57	88.57
12	135.96	96.26
13	140.58	103.27

*** 1.356 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.74	60.74
3	57.68	59.59
4	67.68	59.54
5	77.62	60.60
6	87.38	62.77
7	96.84	66.00
8	105.89	70.27
9	114.40	75.51
10	122.28	81.67
11	129.42	88.67
12	135.75	96.42
13	140.14	103.22

*** 1.357 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.76	60.83
3	57.70	59.74
4	67.70	59.74
5	77.64	60.83
6	87.41	62.99
7	96.88	66.20
8	105.94	70.43
9	114.49	75.61
10	122.43	81.70
11	129.65	88.61
12	136.08	96.27
13	140.78	103.29

*** 1.358 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.73	60.71
3	57.67	59.53
4	67.67	59.48
5	77.61	60.55
6	87.37	62.74
7	96.82	66.01
8	105.84	70.32
9	114.32	75.62
10	122.15	81.84
11	129.22	88.91
12	135.46	96.72
13	139.50	103.16

*** 1.362 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.91	61.64
3	57.89	61.08
4	67.89	61.32
5	77.83	62.36
6	87.67	64.19
7	97.32	66.80
8	106.73	70.18
9	115.84	74.30
10	124.59	79.14
11	132.93	84.66
12	140.80	90.84
13	148.15	97.62
14	154.72	104.75

*** 1.364 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.88	61.44
3	57.86	60.78
4	67.85	61.02
5	77.79	62.16
6	87.58	64.19
7	97.15	67.09
8	106.42	70.84
9	115.32	75.41
10	123.76	80.76
11	131.70	86.85
12	139.05	93.63
13	145.76	101.04
14	148.02	104.05

*** 1.366 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	44.00	65.38
2	53.77	63.26
3	63.71	62.18
4	73.71	62.15
5	83.66	63.19
6	93.44	65.26
7	102.95	68.36
8	112.08	72.45
9	120.72	77.47
10	128.79	83.39
11	136.18	90.12
12	142.83	97.59
13	147.40	103.98

*** 1.367 ***

Failure Surface Specified By 15 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	38.00	63.00
2	47.92	61.71
3	57.90	61.17
4	67.90	61.38
5	77.85	62.35
6	87.70	64.07
7	97.40	66.53
8	106.88	69.71
9	116.09	73.59
10	124.98	78.17
11	133.51	83.40
12	141.61	89.26
13	149.25	95.71
14	156.38	102.72
15	158.49	105.14

*** 1.367 ***

After the program generates the plotting file, the user can run the PLOTSTBL.EXE routine to have a graphical display of the results on a color or enhanced color monitor before using the HP-7470A or HP-7475A plotters. A sample session follows:

A> plotstbl

PCSTABL4M
OUTPUT PLOTTING

PLOTSTBL.EXE from Purdue University (c) 1987

Integrated Screen Graphics Output

```
=====
Filename to be Plotted           ? ex1.plt
First Line of Title              ? Example 1
Second Line of Title             ? by J.E. Thomaz
Screen No. (2=CGA, 9=EGA, 10=Mono EGA) [9]? 9
```

```
-----
| Press `` after plot for options, or RETURN for next plot. |
|-----|
-----
```

```
Minimum X = 0           Maximum X = 300
Minimum Y = 0           Maximum Y = 187.5
Enter Interval for Axes [ 37.5 ]      ? <return>
Enter Number of X intervals [ 8 ]     ? <return>
```

*** (At this point the results are plotted on screen) ***

```
Ready... Press [/] for options...
/ Quit Plotter Title Intervals One-surf Next-plot-#. (this plot =
1.2)....[ 1.2]
```

P

Hit return when ready to plot....

Do You Want to be Prompted for Pen Changes? (y/n) :? n

Plotter (2 Pen or 6 Pen)

? 2

/ Quit Plotter Title Intervals One-surf Next-plot-#.(this plot =
1.2)....[1.2]

Q

Do you want to plot another file (y/n)? n

A>

*** (At this point the user is back in DOS) ***

Figure A12: Surfaces Generated

Figure A13: 10 Most Critical Surfaces

Example 2

This example demonstrates the use of tiebacks for stabilizing an unstable earth slope. As seen in Figure A14, the slope consists of a layer of compacted fill over a till deposit. Above the bedrock and below the till layer is a weak clay layer through which the slide movement is occurring. The crest of the slope is subjected to an inclined and vertical surcharge load. In addition, portion of the slope is saturated by a groundwater table.

A stability analysis using the BLOCK2 option was chosen because the slope has been observed to be moving for several years in an apparent block type failure. The slope is in a siesmically active area., so the pseudo-static earthquake option has also been chosen. The solution to the failure that is being analyzed is the placement of a single row of tiebacks into the slope which anchor into the bedrock.

The input file is described bellow. The comments in parentheses are not part of the file, but comments included to help the user understand the structure of the file.

Figure A14: Example 2 Geometry

Input File:

PROFIL	(Initialization)
TIEBACK EXAMPLE PROBLEM #2	(title)
14 8	
0.0 24.0 12.0 24.0 2	
12.0 24.0 19.5 30.0 2	
19.5 30.0 19.6 31.5 5	
19.6 31.5 22.5 34.0 5	
22.5 34.0 24.0 34.0 5	
24.0 34.0 34.0 42.0 2	
34.0 42.0 46.0 52.0 1	(Geometry description)
46.0 52.0 100.0 52.0 1	
34.0 42.0 100.0 42.0 2	
24.0 34.0 25.5 32.5 5	
19.5 30.0 20.8 28.6 2	
20.8 28.6 25.5 32.5 2	
0.0 16.0 100.0 25.0 3	
0.0 8.0 100.0 20.0 4	
SOIL	(Soil parameter definition)
5	
120. 125. 400. 26. 0. 0. 1	
122. 127. 850. 30. 0. 0. 1	
115. 120. 475. 0. 0. 0. 1	
144. 147. 0. 45. 0. 0. 1	
150. 150. 0. 0. 0. 0. 1	
ANISO	(anisotropic parameters)
1	
2 2	
-30. 600. 34.	
90. 300. 28.	
WATER	(Piezometric Line definition)
1 3 62.4	#3 -> average model
80. 24.	
12. 24.	
26. 30.	
38. 34.	
49. 37.	
58. 39.	
70. 40.	
100. 40.	
EQUAKE	(Earthquake loads)
.02 .02 0.	
LOADS	(External Loads)
2	
50. 56. 100. 10.	
56. 66. 200. 0.	
TIES	(Tieback load)
1	
4 32.5 300000. 10. 40. 45.	

BLOCK2

2

0.5

25 2 6.

22. 14.5 24. 14.5 7.

70. 19.5 72. 19

(Block Search with
user entered correction factor
k=0.5 for Janbu's Method)

The output file generated is listed below.

**** PCSTABLAM ****

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 7/30/88
Time of Run: 5 pm
Run By: Thomaz
Input Data Filename: ex2.in
Output Filename: ex2.out
Plotted Output Filename: ex2.plt

PROBLEM DESCRIPTION TIEBACK EXAMPLE PROBLEM #2

BOUNDARY COORDINATES

8 Top Boundaries
14 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below Bnd
1	.00	24.00	12.00	24.00	2
2	12.00	24.00	19.50	30.00	2
3	19.50	30.00	19.60	31.50	5
4	19.60	31.50	22.50	34.00	5
5	22.50	34.00	24.00	34.00	5
6	24.00	34.00	34.00	42.00	2
7	34.00	42.00	46.00	52.00	1
8	46.00	52.00	100.00	52.00	1
9	34.00	42.00	100.00	42.00	2
10	24.00	34.00	25.50	32.50	5
11	19.50	30.00	20.80	28.60	2
12	20.80	28.60	25.50	32.50	2
13	.00	16.00	100.00	25.00	3
14	.00	8.00	100.00	20.00	4

ISOTROPIC SOIL PARAMETERS

5 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param. (psf)	Pressure Constant (psf)	Piez. Surface No.
1	120.0	125.0	400.0	26.0	.00	.0	1
2	122.0	127.0	850.0	30.0	.00	.0	1
3	115.0	120.0	475.0	.0	.00	.0	1
4	144.0	147.0	.0	45.0	.00	.0	1
5	150.0	150.0	.0	.0	.00	.0	1

ANISOTROPIC STRENGTH PARAMETERS

1 soil type(s)

Soil Type 2 Is Anisotropic

Number Of Direction Ranges Specified = 2

Direction Range No.	Counterclockwise Direction Limit (deg)	Cohesion Intercept (psf)	Friction Angle (deg)
1	-30.0	600.0	34.0
2	90.0	300.0	28.0

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

THE POREPRESSURE MODEL CHOSEN IS:

Average of Hydrostatic/Perpendicular

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 8 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	24.00
2	12.00	24.00
3	26.00	30.00
4	38.00	34.00
5	49.00	37.00
6	58.00	39.00
7	70.00	40.00
8	100.00	40.00

A Horizontal Earthquake Loading Coefficient
Of .020 Has Been Assigned

A Vertical Earthquake Loading Coefficient
Of .020 Has Been Assigned

Cavitation Pressure = .0 psf

BOUNDARY LOAD(S)

2 Load(s) Specified

Load No.	X-Left (ft)	X-Right (ft)	Intensity (lb/sqft)	Deflection (deg)
1	50.00	56.00	100.0	10.0
2	56.00	66.00	200.0	.0

NOTE - Intensity Is Specified As A Uniformly Distributed
Force Acting On A Horizontally Projected Surface.

TIEBACK LOAD(S)

1 Tieback Load(s) Specified

Tieback No.	X-Pos (ft)	Y-Pos (ft)	Load (lbs)	Spacing (ft)	Inclination (deg)	Length (ft)
1	20.76	32.50	300000.0	10.0	40.00	45.0

NOTE - An Equivalent Line Load Is Calculated For Each Row Of Tiebacks Assuming A Uniform Distribution Of Load Horizontally Between Individual Tiebacks.

A user specified value of K for the Janbu
 $f_0 = 1.0 + K [(d/l) - 1.4(d/l)^2]$
 expression was used: K = .500

A Critical Failure Surface Searching Method, Using A Random Technique For Generating Sliding Block Surfaces, Has Been Specified.

The Active And Passive Portions Of The Sliding Surfaces Are Generated According To The Rankine Theory.

25 Trial Surfaces Have Been Generated.

2 Boxes Specified For Generation Of Central Block Base

Length Of Line Segments For Active And Passive Portions Of Sliding Block Is 6.0

Box No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Height (ft)
1	22.00	14.50	24.00	14.50	7.00
2	70.00	19.50	72.00	19.50	5.00

Following Are Displayed The Ten Most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By The Modified Janbu Method * *

Failure Surface Specified By 15 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	5.22	24.00
2	6.11	23.49
3	11.31	20.49
4	16.50	17.49
5	17.98	16.00
6	22.22	11.76
7	70.01	18.08
8	74.26	22.32
9	74.65	22.72
10	77.65	27.91
11	80.65	33.11
12	83.65	38.31
13	85.79	42.00
14	88.96	47.09
15	92.03	52.00

*** 1.527 ***

Individual data on the 32 slices

Slice No.	Width Ft(m)	Weight Lbs(kg)	Water Force	Water Force	Tie Force	Tie Force	Earthquake		
			Top Lbs(kg)	Bot Lbs(kg)	Norm Lbs(kg)	Tan Lbs(kg)	Force Hor Lbs(kg)	Force Ver Lbs(kg)	Surchage Load Lbs(kg)
1	.9	29.2	.0	16.5	.0	.0	.6	.6	.0
2	5.2	1329.6	.0	754.4	4.0	1.4	26.6	26.6	.0
3	.7	327.7	.0	185.9	63.8	21.5	6.6	6.6	.0
4	4.5	3981.5	.0	1849.0	1307.1	105.4	79.6	79.6	.0
5	1.5	2124.7	.0	1145.3	765.5	486.0	42.5	42.5	.0
6	1.5	2675.0	.0	1438.4	808.5	639.1	53.5	53.5	.0
7	.1	204.9	.0	104.2	52.7	46.1	4.1	4.1	.0
8	1.2	2804.2	.0	1340.9	620.7	584.7	56.1	56.1	.0
9	1.4	3800.2	.0	1809.8	696.8	751.2	76.0	76.0	.0
10	.3	781.4	.0	266.0	141.7	-7.7	15.6	15.6	.0
11	1.5	4238.2	.0	1473.9	808.1	-9.0	84.8	84.8	.0
12	1.5	4231.7	.0	1512.6	857.8	53.0	84.6	84.6	.0
13	.5	1432.9	.0	512.8	294.3	32.5	28.7	28.7	.0
14	8.0	25759.9	.0	8870.7	4867.1	1542.7	515.2	515.2	.0
15	4.0	14884.5	.0	4724.0	2113.5	1286.3	297.7	297.7	.0
16	8.0	33858.5	.0	10069.9	3261.0	2935.8	677.2	677.2	.0
17	3.0	13646.9	.0	3917.1	930.0	1085.8	272.9	272.9	.0
18	1.0	4519.7	.0	1336.4	280.2	354.4	90.4	90.4	.0
19	6.0	26795.2	.0	8134.7	1412.3	2026.6	535.9	535.9	600.0
20	2.0	8808.6	.0	2755.8	388.2	632.6	176.2	176.2	400.0
21	8.0	34615.0	.0	11197.2	1235.7	2313.8	692.3	692.3	1600.0
22	4.0	16921.7	.0	5525.0	479.1	1036.8	338.4	338.4	.0
23	.0	54.8	.0	18.0	1.4	3.3	1.1	1.1	.0
24	4.2	16726.8	.0	7413.1	1314.9	806.9	334.5	334.5	.0
25	.4	1455.3	.0	612.9	112.1	77.0	29.1	29.1	.0
26	3.0	9926.3	.0	5497.4	1268.2	528.2	198.5	198.5	.0
27	3.0	7946.5	.0	3551.9	1083.6	577.4	158.9	158.9	.0
28	3.0	5966.8	.0	1606.5	909.1	590.2	119.3	119.3	.0
29	1.0	1516.3	.0	103.2	261.8	190.1	30.3	30.3	.0
30	1.2	1526.5	.0	.0	289.0	221.8	30.5	30.5	.0
31	3.2	2844.7	.0	.0	637.0	578.6	56.9	56.9	.0
32	3.1	904.5	.0	.0	505.7	518.9	18.1	18.1	.0

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	4.88	24.00
2	5.82	23.46
3	11.02	20.46
4	16.21	17.46
5	18.23	15.44
6	22.48	11.19
7	71.22	19.90
8	73.98	22.66
9	76.98	27.85
10	79.98	33.05
11	82.98	38.25
12	85.14	42.00
13	88.32	47.09
14	91.39	52.00

*** 1.532 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	5.71	24.00
2	6.54	23.52
3	11.73	20.52
4	16.93	17.52
5	18.13	16.33
6	22.37	12.08
7	71.64	20.30
8	74.00	22.66
9	77.00	27.86
10	80.00	33.05
11	83.00	38.25
12	85.17	42.00
13	88.35	47.09
14	91.42	52.00

*** 1.579 ***

Failure Surface Specified By 15 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	6.61	24.00
2	7.32	23.59
3	12.51	20.59
4	17.71	17.59
5	19.27	16.03
6	23.51	11.79
7	70.36	17.63
8	74.61	21.87
9	75.53	22.80
10	78.53	27.99
11	81.53	33.19
12	84.53	38.39
13	86.62	42.00
14	89.80	47.09
15	92.87	52.00

*** 1.593 ***

Failure Surface Specified By 15 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	6.73	24.00
2	7.42	23.60
3	12.62	20.60
4	17.81	17.60
5	19.57	15.85
6	23.81	11.60
7	70.49	18.16
8	74.73	22.40
9	75.09	22.76
10	78.09	27.95
11	81.09	33.15
12	84.09	38.35
13	86.20	42.00
14	89.38	47.09
15	92.45	52.00

*** 1.599 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	7.30	24.00
2	7.91	23.65
3	13.10	20.65
4	18.30	17.65
5	18.80	17.15
6	23.04	12.90
7	70.19	21.82
8	70.73	22.37
9	73.73	27.56
10	76.73	32.76
11	79.73	37.95
12	82.07	42.00
13	85.25	47.09
14	88.32	52.00

*** 1.693 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	7.70	24.00
2	8.26	23.68
3	13.45	20.68
4	18.65	17.68
5	18.71	17.61
6	22.96	13.37
7	70.17	19.19
8	73.60	22.62
9	76.60	27.82
10	79.60	33.02
11	82.60	38.21
12	84.79	42.00
13	87.97	47.09
14	91.04	52.00

*** 1.732 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	7.50	24.00
2	8.08	23.66
3	13.28	20.66
4	18.47	17.66
5	22.46	13.68
6	70.62	21.63
7	71.42	22.43
8	74.42	27.62
9	77.42	32.82
10	80.42	38.02
11	82.72	42.00
12	85.90	47.09
13	88.97	52.00

*** 1.736 ***

Failure Surface Specified By 13 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	7.42	24.00
2	8.01	23.66
3	13.21	20.66
4	18.40	17.66
5	22.26	13.80
6	71.20	19.61
7	74.28	22.68
8	77.28	27.88
9	80.28	33.08
10	83.28	38.27
11	85.43	42.00
12	88.61	47.09
13	91.68	52.00

*** 1.752 ***

Failure Surface Specified By 14 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	8.88	24.00
2	9.28	23.77
3	14.47	20.77
4	19.67	17.77
5	23.72	13.72
6	70.74	18.35
7	74.98	22.59
8	75.15	22.76
9	78.15	27.96
10	81.15	33.16
11	84.15	38.35
12	86.26	42.00
13	89.44	47.09
14	92.51	52.00

*** 1.803 ***

Figure A15: Surfaces Generated

EXAMPLE 2

Figure A16: 10 Most Critical Surfaces

OTHER REFERENCES

- Carpenter, J.(1984); "Slope Stability Analysis With STABL4", Joint Highway Research Project No. 84-19, School of Civil Engineering, Purdue University, West Lafayette, Indiana.
- Carpenter, J.(1985); "STABL5... The Spencer Method of Slices: Final Report", Joint Highway Research Project No. 85-17, School of Civil Engineering, Purdue University, West Lafayette, Indiana.
- Hoek, E. and Bray, J.W. (1974); "Rock Slope Engineering", Inst. of Min. and Met., London, 310 pages. Second Revision in 1977,402.
- Humphrey, D. and Holtz,R. (1986); "STABL6 With Reinforcing Layer Option"; Joint Highway Research Project No. 86-18, School of Civil Engineering, Purdue University, West Lafayette, Indiana.
- Janbu, N. (1954); "Stability Analysis of Slopes with Dimensionless Parameters", Harvard University Soil Mechanics Series No.46.
- Janbu, N. (1957); "Earth Pressure and Bearing Capacity Calculations by Generalized Procedure of Slices", Proc. 4th Int. Conf. Soil Mech. Found. Eng., Volume 2, pp. 207-212.

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