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## PIT SLOPE MANUAL

supplement 5-1

## PLANE SHEAR ANALYSIS

This supplement has been prepared as part of the

PIT SLOPE PROJECT

of the

Mining Research Laboratories  
Canada Centre for Mineral and Energy Technology  
Energy, Mines and Resources Canada

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## THE PIT SLOPE MANUAL

The Pit Slope Manual consists of ten chapters, published separately. Most chapters have supplements, also published separately. The ten chapters are:

1. Summary
2. Structural Geology
3. Mechanical Properties
4. Groundwater
5. Design
6. Mechanical Support
7. Perimeter Blasting
8. Monitoring
9. Waste Embankments
10. Environmental Planning

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## ABSTRACT

The purpose of this supplement is to provide methods of analyzing slope instability arising from sliding on discontinuities, that are feasible at the present time. A description of graphical methods is included because many cases can be adequately handled that way and also because they provide an understanding of the essentials for making good use of the computer programs.

The simplest case of plane shear instability is that of sliding along a single plane. The method of analysis is simple, the main difficulty being to obtain adequate input data. The attitude of the plane throughout the slope, its roughness, its shear strength properties, and the ground water conditions affecting it, all require intensive site investigations. A variation of this problem is when sliding can occur along a series of planes of one set assisted by a set of cross joints making up what is called a stepped-path. Again the major effort required is in obtaining data on the discontinuities such as length, spac-

ing, areal distribution, and the strength of any connecting rock substance between discontinuities.

In some cases, sliding can involve the interaction of two blocks along one or two planes. Analyses are presented for cases where strike of the planes is substantially parallel to the face of the slope.

Where the strike of the discontinuities that can be sliding planes is oblique to the slope face, single plane sliding or the above two-block case are less probable. Analysis is required to determine if there are planes that can combine to form a 3-D wedge with an angle of intersection sufficiently steep to cause sliding. Once the geometry and strength properties are known, graphical deterministic analyses for such cases are straightforward. To determine probabilities of instability, a computer solution is almost always required.

Appendix A provides a computer program, PLAFAM, for analyzing the single plane or stepped-path mode of instability. The probability of in-

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stability schedules are determined by using the Monte Carlo approach, ie, the simulated sampling of geometric and strength properties for repeatedly calculating instability, and statistically appraising the results.

Appendix B provides documentation of the computer program TWOBAM for the analysis of two-block sliding. Analysis of such a system is somewhat more complex than for conventional plane shear stability having to be expressed as the ratio of weights of the active and passive blocks. Probability schedules are produced using the Monte Carlo approach.

Appendix C provides documentation for WINTAM, a 3-D wedge analysis program. The analysis is essentially of a rigid body sliding down the line of intersection formed by two planes or discontinuities. Probability schedules are obtained using the Monte Carlo approach.

Appendix D contains program documentation

for GENSAM, a general slip surface analysis. In some cases of potential instability sliding, if sliding occurs, it will be along two planes, both striking parallel to the slope face but dipping into the pit at different angles. Also, as a result of various geologic inhomogeneities, the shape of the slip surface can be even more complex. GENSAM is a method of analysis, similar to the traditional slices method for rotational sliding, which can be applied to bilinear and curved surfaces of any nature. It can, of course, also be used for circular surfaces and thus provides an alternate approach for the cases described in Supplement 5-2. Probability schedules are obtained using the Monte Carlo approach.

Appendix E provides program documentation for MONTEC, the Monte Carlo subroutines that are used in all the above stability programs. The package of subroutines perform random sampling and statistical calculations and plot the results.

## ACKNOWLEDGEMENTS

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G. Major, H-S. Kim and D. Ross-Brown wrote the supplement. R. Sage edited the appendices.

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## INTRODUCTION

1. In this supplement programs are described for analyzing stability of slopes with potential plane shear sliding.

2. Slides in a jointed rock mass depend upon the relative orientations of the discontinuities within the rock mass with respect to the slope face. By using spherical projection it is possible to determine which mechanisms of sliding are kinematically possible. This test forms the basis for deciding which analysis techniques should be used.

### Spherical Projections

3. Spherical projection is a method of representing three-dimensional data on a plane. The intersections of planes and lines with a reference sphere are projected onto a flat surface. Planes project as lines, and lines project as points. It is usual to use only the lower hemisphere.

4. Several methods of projection are available. For the equal area projection, a unit area anywhere on the projection plane represents the same fraction of the total area of the reference hemisphere. This enables the density of plotted

points to be determined on the projection using a counter of fixed area. This method of projection is shown in Fig 1. For the equal angle or conformal projection, shapes on the reference hemisphere maintain their true shape on the projection. This property is useful when dealing with specific shapes such as friction circles. The method of projection is shown in Fig 2.

5. Reference hemispheres use intersections of horizontal planes and vertical planes passing through the centre to produce polar nets (Fig 3). Circles on the reference hemisphere defined by planes which pass through the centre of the hemisphere are termed great circles. Graduations on the hemisphere are defined by the family of east-west vertical planes and the family of north-south planes which pass through the centre defining great circles for equatorial nets. Equal angle or stereographic equatorial nets are sometimes termed Wulff nets (Fig 4). Equal area equatorial nets are sometimes called Schmidt nets (Fig 5).

6. Equatorial nets are used with transparent overlays. To plot the orientation of a line, the direction is first marked by measuring around the

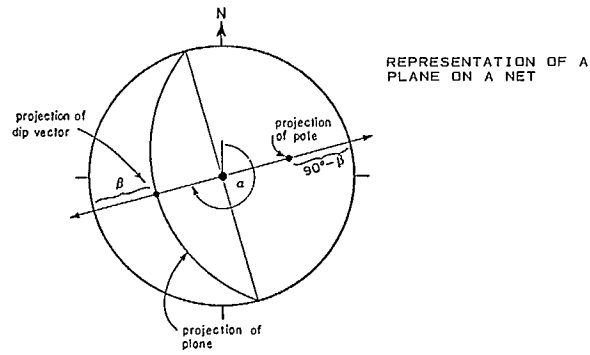
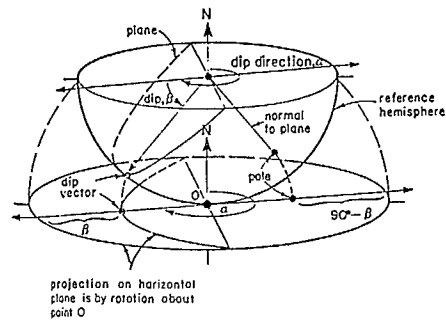
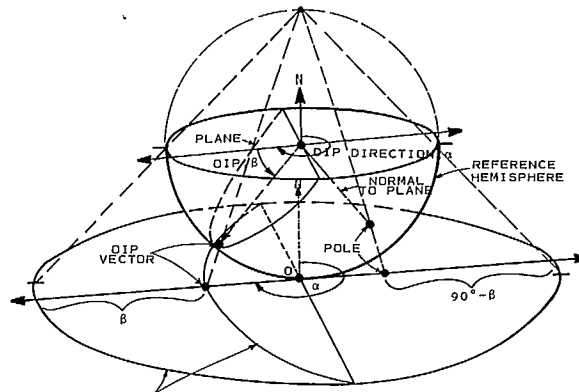


Fig 1 - Lower hemisphere equal area projection.



PROJECTION TO A HORIZONTAL PLANE IS BY EXTENSION OF THE LINE THROUGH THE ZENITHAL POINT OF THE REFERENCE SPHERE.

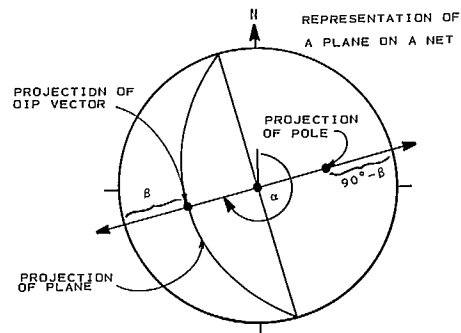


Fig 2 - Lower hemisphere equal angle projection.

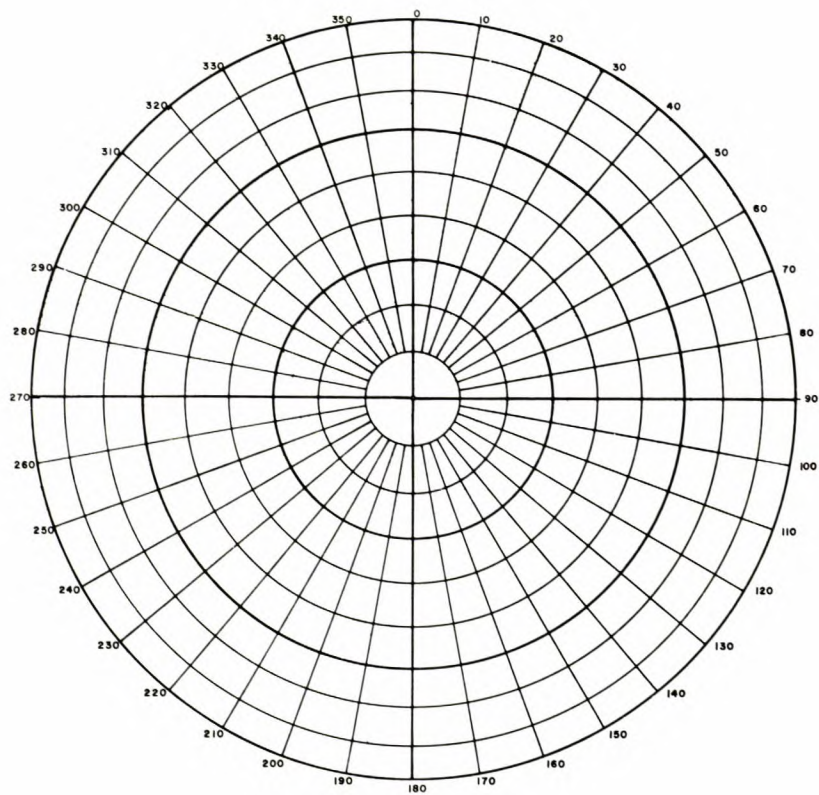


Fig 3 - Polar net.

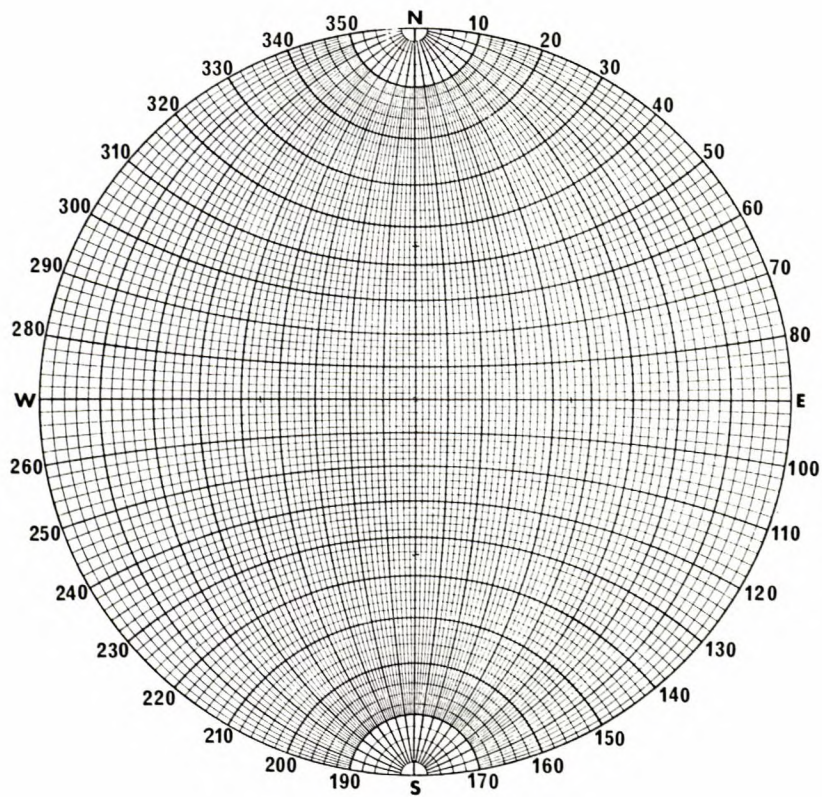


Fig 4 - Wulff net.



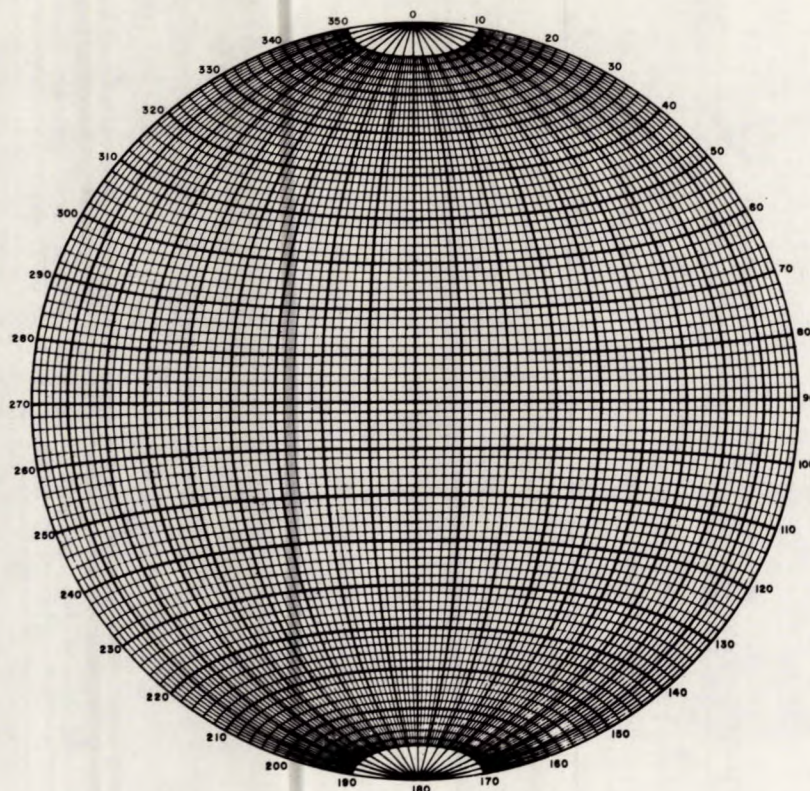


Fig 5 - Schmidt net.

circumference of the net. The overlay is then rotated until this point lies on the east-west axis of the net, and its dip is measured using the graduations along this great circle. If the line is the dip vector of a plane, the great circle which uniquely defines that plane can be traced as the great circle on the net which crosses the east-west axis at the orientation of the dip vector. The normal or pole to this plane is located by counting  $90^\circ$  from the dip vector along the east-west axis. Rotating the overlay back to its original position gives the correct representation of the orientation of the line or plane.

#### Sliding Modes

7. For simple plane shear to occur, a discontinuity must dip at an angle less than the slope face and in a direction close to that of the slope face, as shown in Fig 6. The simplifying assumption is often made that a single value (the mean value) can be used to define the orientation

of the discontinuity. In reality, orientations will vary about this value. This means that for any slope angle sliding may be possible. Analysis of the variations is required, even if the mean orientation dips more steeply than the slope face.

8. A special case of simple plane shear occurs when individual discontinuities are not long enough to provide a single continuous sliding surface. A set of cross joints is required to connect the major discontinuities to form a sliding surface.

9. The characteristic spherical projection for this type of sliding is shown in Fig 7. The cross joints can dip in the opposite direction to the slope face.

10. Two-block sliding, in which a wedge of rock produces an active force on a second wedge of rock which would otherwise be stable, can occur in rock slopes where several joint sets dipping in various directions form active and passive wedges.

11. A typical arrangement of joints is shown in Fig 8. The dip of Plane 2 must be sufficiently

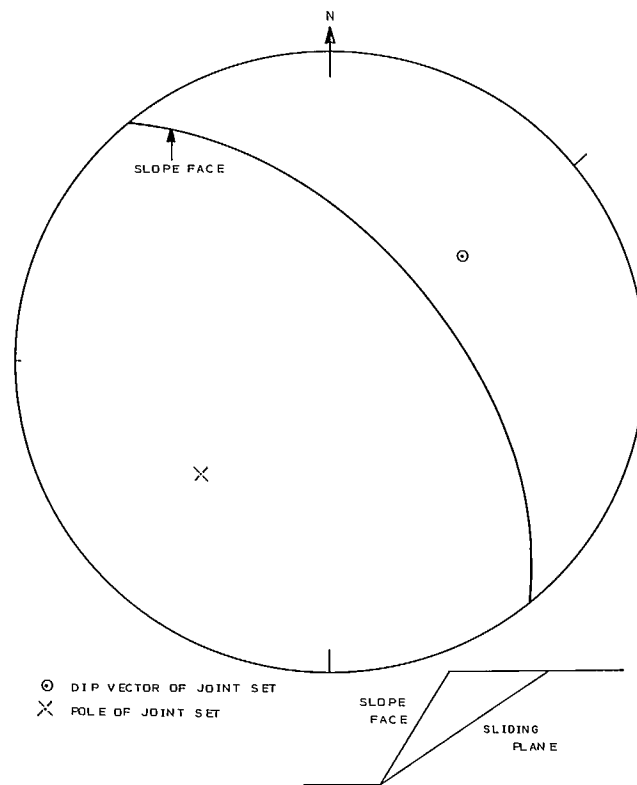


Fig 6 - Characteristic spherical projection for simple plane shear.

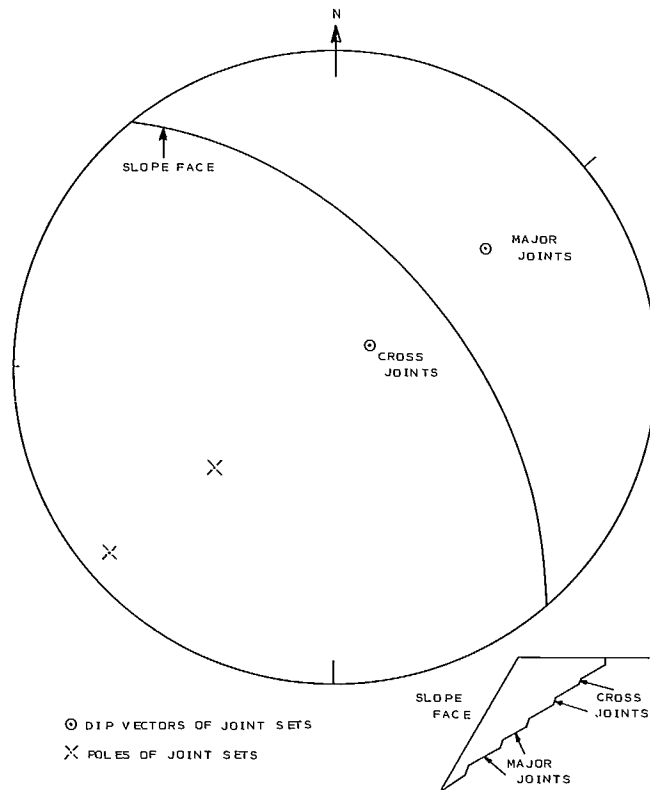


Fig 7 - Characteristic spherical projection for a stepped-path.

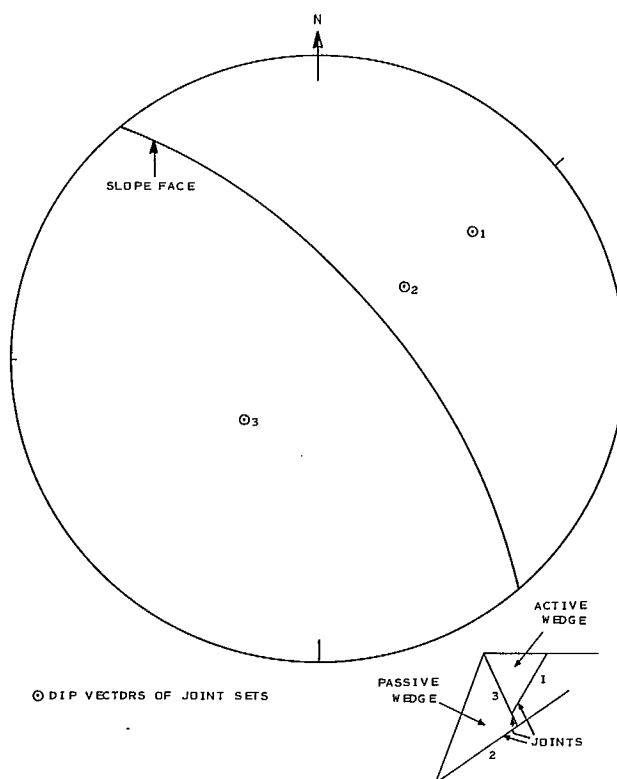


Fig 8 - Characteristic spherical projection for two-block sliding.

low to ensure that the passive wedge alone will remain stable on Plane 2.

12. Discontinuities can intersect such that sliding can occur along the line of intersection of the two joints. The characteristic spherical projection for this type of slide, commonly known as a 3-d-wedge, is shown in Fig 9. Sliding is kinematically possible when the dip of the line of intersection of the joints is less than that of the slope face.

13. Sliding can occur along surfaces which do not correspond to any of the previously defined categories (Fig 10). This is possible when one or more of the following conditions exist:

- a. The rock mass exhibits random jointing or is highly fractured throughout. In this case the characteristic spherical projection will show a wide scatter of orientations.
- b. The rock mass is very weak so that its properties approach those of a soil.
- c. Very high slopes exist in closely jointed rock, where the shear strength of the rock substance

can be the critical factor for slope stability.

d. A specific discontinuity, such as a fault, is known to exist which could cause a non-linear sliding surface.

14. The sliding surface in the first three of these cases is frequently approximated by the arc of a circle. This is a special case of the general slip surface program.

15. Traditionally, the stability of slopes has been analyzed and the results expressed in terms of a factor of safety. This is usually defined as the ratio of the forces tending to disturb the equilibrium of the slope to those available for preventing movement of the slope. The factor of safety, which is 1.0 for the case of limiting equilibrium, may be calculated using the mean values of the input parameters. Because of the uncertainty associated with the input variables, a factor of safety greater than 1.0 has always been necessary to ensure an acceptably low chance of instability. Moreover, a given factor of safety will not always correspond to the same

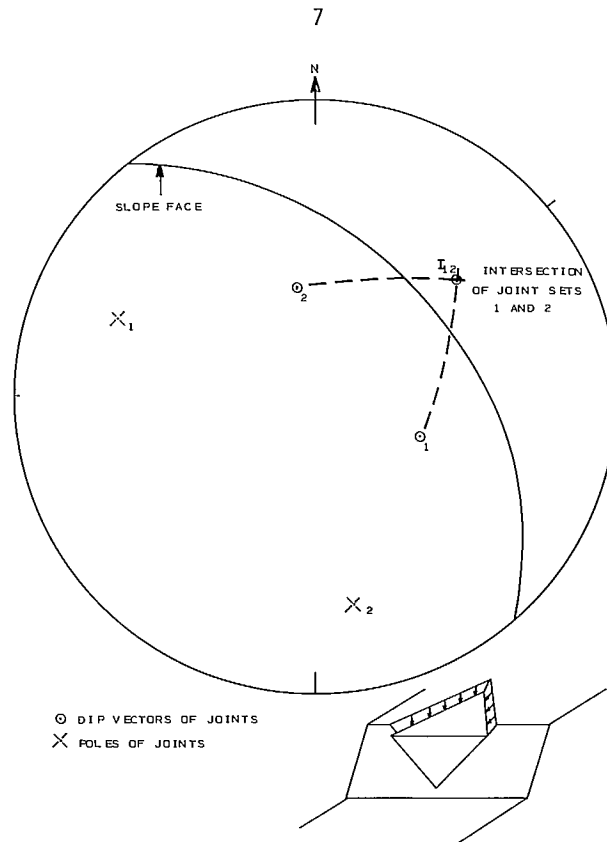


Fig 9 - Characteristic spherical projection for 3-d-wedge sliding.

chance of instability.

16. Sensitivity to changes in input values is determined by varying the critical parameters either singly or in combination. This information is used to supplement engineering judgment in determining whether likely variations in parameters are significant.

17. A limitation of this approach is that the factor of safety is indeterminate when the geometry of the potential sliding block is kinematically impossible. The uncertainty associated with the orientations may mean that sliding is kinematically possible for a certain percentage of the length of the slope.

18. A more recent approach to this problem has been to express the stability of a slope in terms of the probability that the slope will slide. This probability is determined for various slope angles for different heights. Determination of variations of input parameters requires a careful program of testing and measurement. The results allow mine operators to select a slope angle that

is a financial optimum.

19. Although no analysis method can ever fully replace engineering judgment, a probabilistic analysis can minimize the judgment necessary by correctly accounting for quantifiable uncertainties.

#### Input Data

20. A coordinate system must be specified for the slope section in terms of x and y coordinates.

21. The input data should be in consistent units. The programs described in the appendices can be used with any system of units.

22. Data is input in the following groups:

- a. slope geometry,
- b. internal geometry ( eg location of discontinuities and profile lines separating different material types),
- c. tension crack,
- d. material properties (eg density, strength of rock substances and shear strengths of discontinuities),

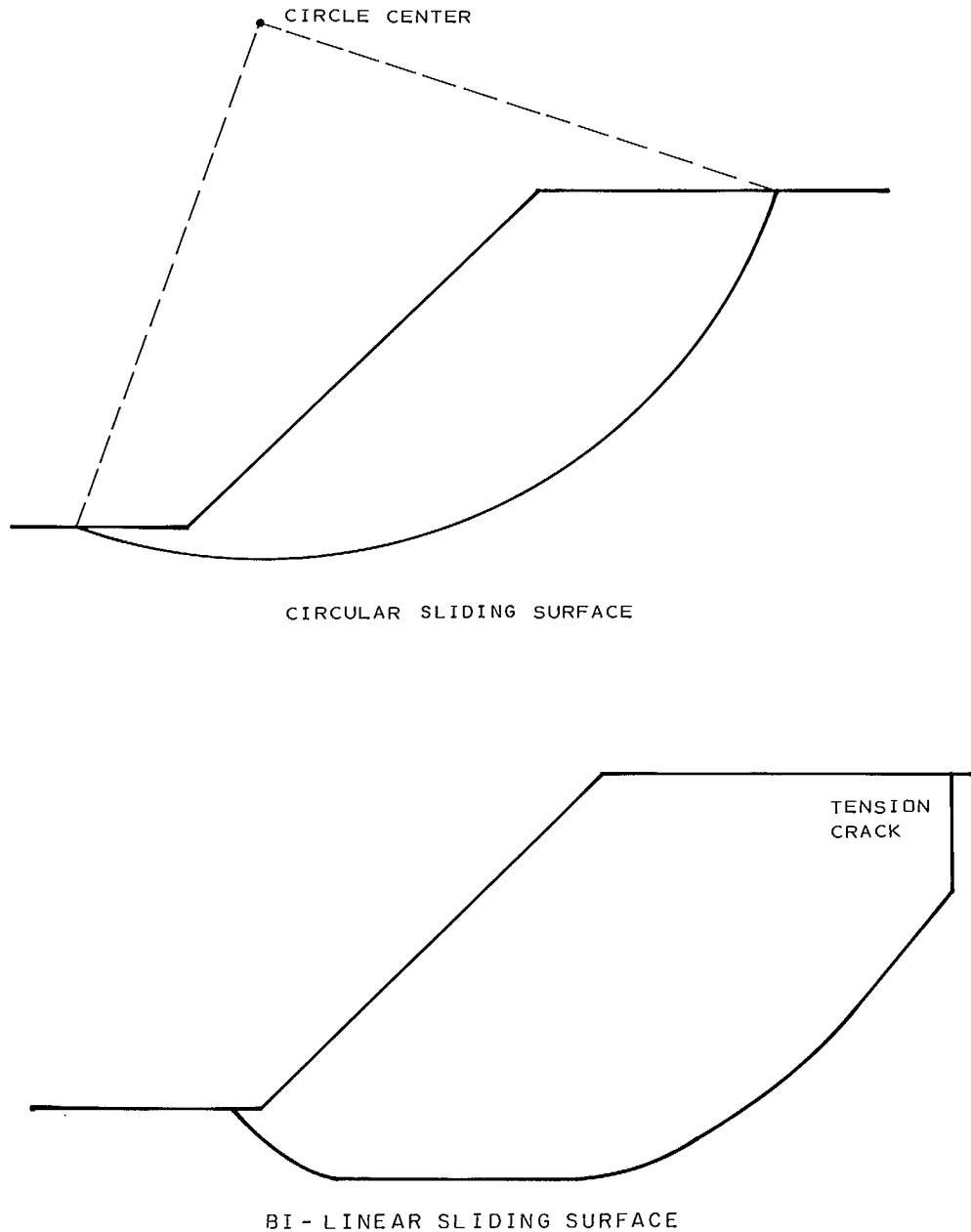


Fig 10 - Sliding along a bi-linear surface.

- e. groundwater (eg piezometric lines and pore pressures), and
- f. external forces (eg surface pressures, rock

anchor forces and earthquake loading).

23. Although the above information summarizes the data needed to define the problem, it will



also be necessary to specify how the problem is to be solved and what kind of output information is required.

#### Probability

24. Once the distributions of the input parameters has been defined, several methods are available for determining the probability of sliding of a slope, which is defined as the probability that the factor of safety will be less than 1.0.

25. One approach is to determine the probability of sliding graphically using spherical projection (1, 2). This has the advantage that no sophisticated mathematics or analysis is necessary so long as: (a) the simplifying assumption that

certain of the input parameters are deterministic is acceptable, (b) no volumes of complicated shapes need to be determined and (c) the mechanism of failure is relatively simple.

26. One general method of determining probabilities is by Monte Carlo. This involves defining the distribution of each input parameter, selecting a value at random from each distribution and using the selected values to calculate the factor of safety. This process is repeated until a distribution of factors of safety sufficient to define the probability of sliding has been accumulated. The large number of repeated calculations necessary in the Monte Carlo approach means that the use of a computer is essential.

## SINGLE PLANE AND STEPPED-PATH SLIDING

### Factor of Safety

27. The factor of safety is the ratio of the forces acting to keep the potential sliding mass in place (the cohesion times the area of the failure surface plus the frictional shear strength determined using the effective normal reaction across the failure plane) to the forces tending to cause the mass to slide (the sum of the components of weight, water forces and other external forces acting along the failure surface). The calculation requires resolving all the forces acting on the potential sliding mass in directions parallel and normal to the potential sliding surface. The factor of safety is:

$$F = \frac{cA + (W \cos \psi_p + T \cos \theta - U - V \sin \psi_p) \tan \phi}{W \sin \psi_p - T \sin \theta + V \cos \psi_p}$$

eq 1

where (see Fig 11)

W is the weight of the sliding block,

A is the area of the sliding surface,

$\psi_p$  is the dip of the sliding surface,

U is the uplift force due to water pressure on the sliding surface,

V is the force due to water pressure in the tension crack,

$\phi$  is the apparent friction angle acting on the sliding surface,

c is the cohesion acting on the sliding surface,

T is an external force acting on the block and

$\theta$  is the angle between the external force and the normal to the sliding surface.

28. Any number of external forces can be included in the equation. The linear approximation for the shear strength envelope, which affects the numerator, is only strictly valid at one normal stress where a curved envelope exists.

29. Example 1. Calculate the factor of safety of the slope shown in Fig 12.

$$A = \frac{(100 + 200 \tan 20^\circ)}{\cos 30^\circ} = 199.5 \text{ ft}^2 (18.5 \text{ m}^2)$$

$$W = \left[ \frac{(100 + 199.5 \cos 30^\circ)}{2} \right] \times 200$$

$$- \frac{172.9 \times 172.9 \tan 30^\circ}{2} \Big] 165$$

$$= 3,077,000 \text{ lbf} (13,687 \text{ kN})$$

$$V = 62.4 \times \frac{(100.2 - 40)^2}{2} = 112,000 \text{ lbf} (498 \text{ kN})$$

$$U = 62.4 \times \frac{(59.8 \times 199.5)}{2} = 372,000 \text{ lbf} (1655 \text{ kN})$$

Substituting these values into eq 1 gives

$$\begin{aligned} FS &= \{3500 \times 199.5 + (3,077,000 \times 0.866 - 372,000 \\ &\quad - 112,000 \times 0.5) 0.4663\} / \{3,077,000 \\ &\quad \times 0.5 + 112,000 \times 0.866\} = 1.06 \end{aligned}$$



30. Example 2. It is required to stabilize the slope analyzed above. Calculate the increase in factor of safety which would result from complete drainage.

31. This is obtained by substitution of the appropriate values calculated in Example 1 into eq 1.

$$FS = \frac{3500 \times 199.5 + (3,077,000 \times 0.866) 0.4663}{3,077,000 \times 0.5}$$

$$= 1.26$$

32. Example 3. If slope stabilization is to be by means of horizontally applied reinforcement, what is the force which must be applied to increase the factor of safety to that resulting from complete slope drainage.

Substituting into eq 1 gives:

$$1.26 = \frac{1,741,000 + T \cos 60^\circ \times 0.4663}{1,635,000 - T \sin 60^\circ}$$

$$T = 242,000 \text{ lbf (1076 kN)}$$

#### Mean Critical Slope Angle

33. Given the mean and standard deviation,  $m_\beta$  and  $s_\beta$ , of the dip,  $\beta$ , of the sliding plane together with  $m$  and  $s$  of the friction angle,  $\phi$ , the cohesion,  $c$ , the maximum annual groundwater height behind the crest,  $D$ , and the height of the slope,  $H$ , the approximate mean critical slope angle,  $i_c$ , can be calculated using the following equation:

$$i_c = \beta + \frac{9420 (c/\gamma H)^{4/3}}{\beta - \phi(1 - 0.1 (D/H)^2)} \quad \text{eq 2}$$

where  $\gamma$  is the rock mass unit weight. The equation is empirical and is based on previous studies (3). It can be useful for preliminary analyses. Alternatively, given a slope angle,  $i$ , the approximate mean critical height, or depth of pit,  $H_c$ , could be calculated as follows:

$$H_c = \frac{956 c}{\gamma[(i - \beta)(\beta - \phi(1 - 0.1(D/H)^2))]^{3/4}} \quad \text{eq 3}$$

34. Example 4. A pit wall is to be 500 ft (152 m) high. The mean maximum height of the

regional groundwater table is 400 ft (122 m). The mean rock mass density is 172.8 pcf (2.77 T/m<sup>3</sup>). Bedding planes dip into the pit at a mean angle of 40°. The mean apparent angle of friction on the bedding plane is 35°. The mean apparent cohesion is 1440 psf (69 kN/m<sup>2</sup>).

35. From eq 2, the critical mean slope angle is determined as follows:

$$i_c = \frac{40 + 9420 (1440/172.8 \times 500)^{4/3}}{40 - 35 (1 - 0.1 (400/500)^2)} = 45.6$$

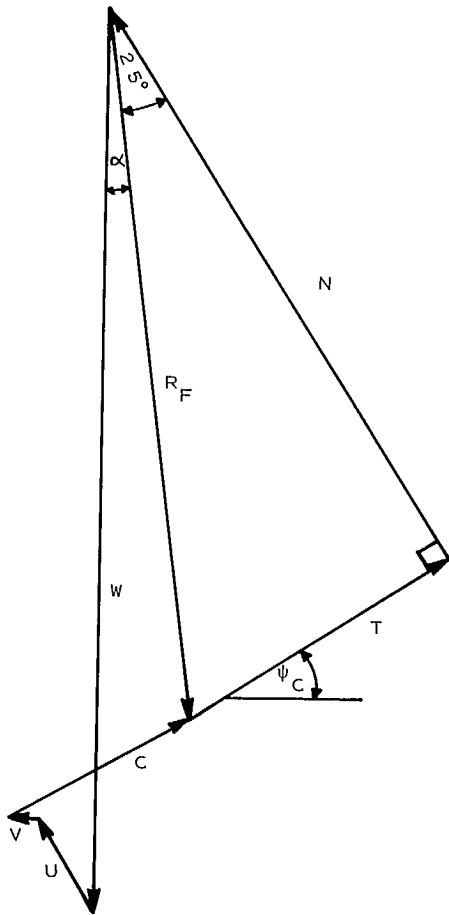
Being based on mean values, a slope 500 ft high at 45.6 would have a 50% probability of instability.

#### Critical Dip

36. A manual method for estimating the probability of sliding which takes account of uncertainty in joint orientations and continuity of the joints can be useful (2,4). The dip of the critical discontinuity at the condition of limiting equilibrium (the "critical dip") is calculated. This requires the assumption that shear strength, rock density, external loads, water pressure and slope geometry are all deterministic and independent of the orientation of the sliding surface, which may not be realistic for water pressure because it means that the water table must be at a constant height above the discontinuity. In other words, the phreatic surface is correlated with the sliding surface. The assumption will usually produce a conservative answer. It may also lead to the physically unrealistic case of the phreatic surface being outside the slope. A more realistic assumption is that the water table remains fixed, and hence the water pressure will vary according to the orientation of the discontinuity.

37. Example 5. For the slope given in Example 1 calculate the probability of sliding if the dip of the discontinuity,  $\beta$ , has a mean value of 30° with a standard deviation of 4°.

38. The forces acting on the potential sliding mass are first calculated either graphically or as shown in Example 1. The force vectors representing the weight, water forces, earthquake forces, external loading and cohesive forces are plotted head to tail as shown in Fig 13. The



SCALE: 1" = 500,000 LBF

Fig 13 - Determination of critical dip.

direction of most of these forces is self-evident. The force due to the cohesion equals the cohesion per unit area times the area of the sliding surface. This acts in the direction of the discontinuity.

39. The unknown forces are the normal and shear forces, although their resultant,  $R_F$ , is known. At the condition of limiting equilibrium, the full shear strength will be mobilized. Therefore, since the normal force and shear force vectors must close the force polygon, the normal force will be at an angle  $\phi$  to the resultant force,  $R_F$ . The direction of the shear force defines the "critical dip",  $\beta_c$ .

40. From the geometry of the force polygon it is evident that  $\beta_c = \phi - \alpha$ , where  $\alpha$  is the angle

that  $R_F$  makes with the vertical as shown in Fig 13.

41. The probability of sliding,  $P_s$ , is based on the distribution of joint dips,  $\beta$ , and is:

$$P_s = P(\beta_c < \beta) \quad \text{eq 4}$$

42.  $P_s$  is represented by the area under the assumed normal distribution curve to the right of the critical dip,  $33^\circ$ , as shown in Fig 14. A table of such areas is included on page 68 of chapter 5. The probability of sliding in this case is 22.7 per cent.

43. The probability of sliding should be multiplied by the probability of occurrence of critical geometry. Such geometry requires a single discontinuity long enough to provide a continuous sliding plane at the required location. The product is then the probability of instability.

44. Because the critical dip can be influenced by the angle of the slope face, it must be recalculated for each trial slope angle.

45. Direct shear tests usually produce a shear strength envelope which is curved. It is usual to approximate the curved envelope by a straight line, which is strictly only valid for the normal stress where the linear envelope touches the curved shear strength envelope (Fig 15).

46. The shear strength ( $\tau_1$ ) at a given normal stress ( $\sigma_1$ ) in terms of a friction angle ( $\phi_T$ ) and apparent cohesion ( $c$ ) is:

$$\tau_1 = c + \sigma_1 \tan \phi_T \quad \text{eq 5}$$

47. However, as Fig 15 shows,  $\tau$ , can also be defined in terms of a secant angle of friction,  $\phi_s$ , as:

$$\tau_1 = \sigma_1 \tan \phi_s \quad \text{eq 6}$$

Equating equations 3 and 4 gives

$$\tan \phi_s = \frac{c}{\sigma_1} + \tan \phi_T \quad \text{eq 7}$$

48. Example 6. Calculate the probability of sliding for the slope given in Example 4 using the

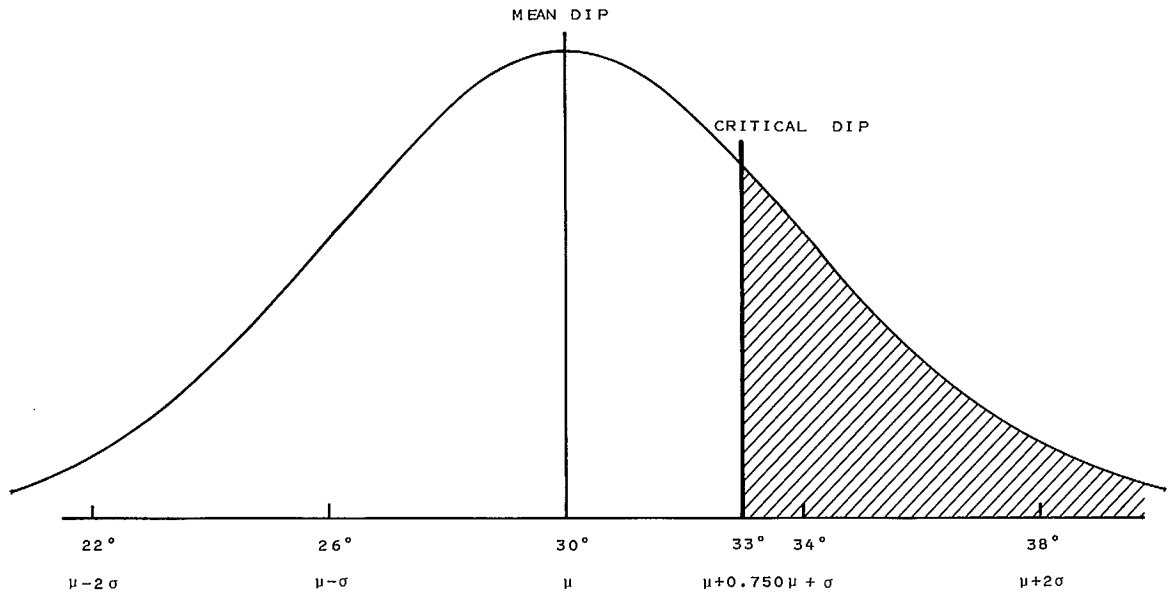


Fig 14 - Calculation of probability of sliding.

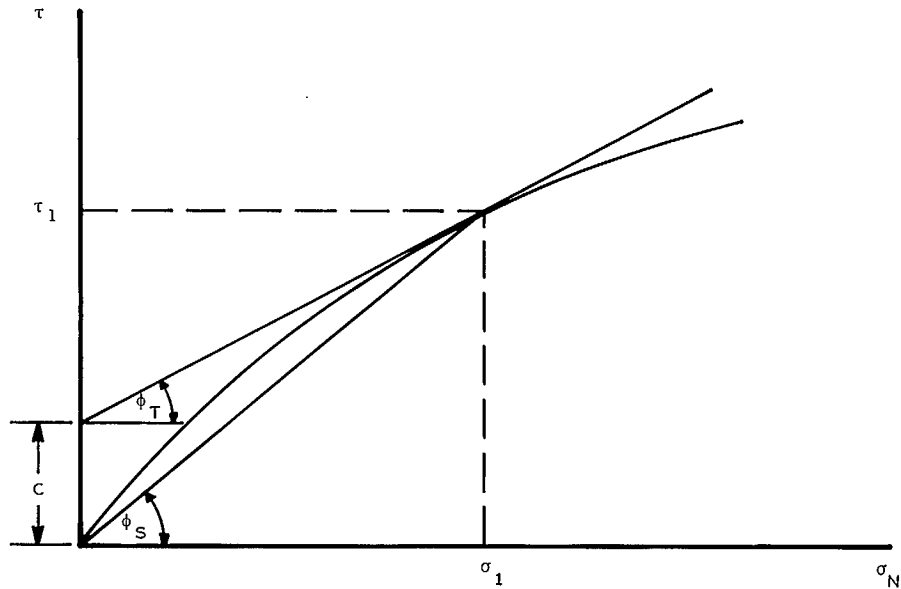


Fig 15 - Relationship between tangent and secant friction angles.

secant angle of friction.

49. The secant angle of friction,  $\phi_s$ , is determined using eq 6. The effective normal stress on the sliding plane is

$$\sigma' = \frac{W \cos \beta - U - V \sin \beta}{A} = \frac{2,237,000}{199.51}$$

$$= 11,200 \text{ lb/ft}^2 (536.2 \text{ kPa})$$

Substituting this value into eq 6 gives

$$\tan \phi_s = \tan 25^\circ + \frac{3,500}{11,200} = 0.778$$

$$\phi_s = 37.9^\circ, \text{ say } 38^\circ$$

50. The force polygon can now be constructed as in Example 4 with the exception that the cohesion is now incorporated into the secant friction angle. This construction is shown in Fig 16, giving  $\alpha = 6^\circ$  and  $\beta_c = 32^\circ$ .

#### Stepped-Path Sliding

51. The case of sliding along a stepped path can be analyzed by determining the mean orientation of the sliding surface,  $\beta$ . Fig 17 shows the way in which sliding will occur by

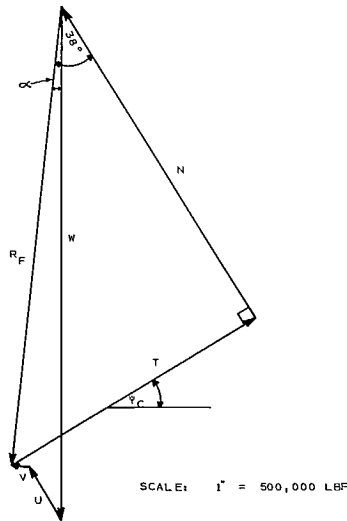


Fig 16 - Determination of critical dip using secant friction angle.

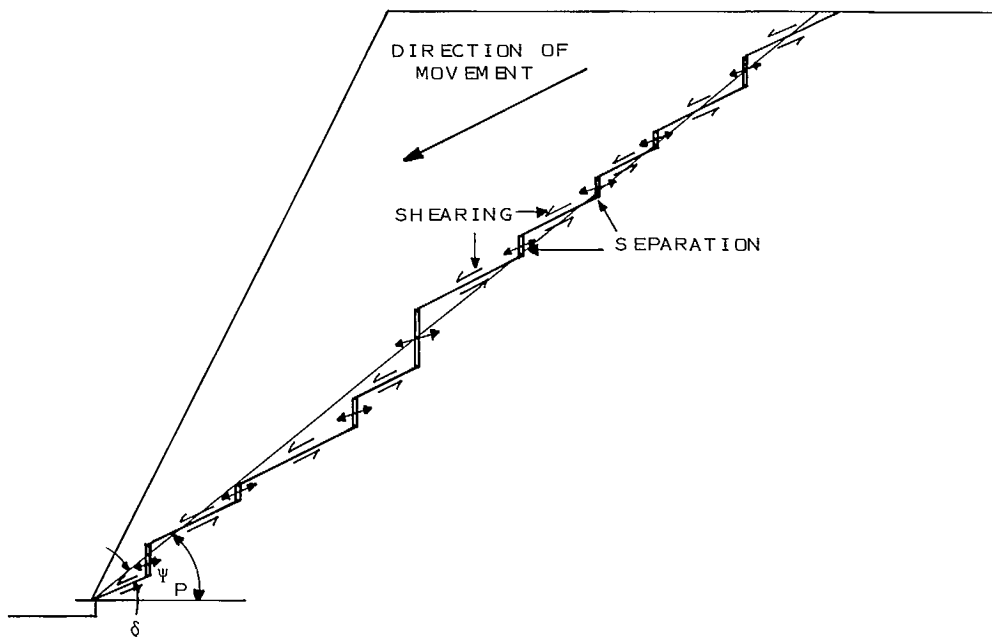


Fig 17 - Sliding along a stepped-path.

shearing along major joints and separation on cross joints. The mean sliding surface,  $\beta$ , dips more steeply than the major joint set by an amount  $\delta$ .

52. For a factor of safety calculation,  $\beta$  is used to determine the weight of the sliding mass and the effect of water pressure. All forces are resolved in the direction of movement, hence the dip of the major joint set is used in eq 1 (5).

53. For a critical dip analysis, the step angle should be added to both the critical dip angle and the dip of the major joints so that eq 4 becomes:

$$P_s = P([\beta_c + \delta] < [\beta_p + \delta]) \quad \text{eq 8}$$

54. The step angle,  $\delta$ , is calculated from mean length,  $M_L$ , and mean spacing,  $M_S$ , of the major joint set:

$$\tan \delta = \frac{M_S}{M_L} \quad \text{eq 9}$$

If spacing and length have log-normal distributions, the geometric means should be used (4). This approach assumes that a cross joint will always exist, running from the end of one major joint to the start of the next which results in a single value for the step angle.

55. A different approach is to calculate  $\delta$  using the distributions of joint lengths, dips, and spacings determined from field investigations. A stress criterion for failure through intact rock (6), Monte Carlo simulation can be used to determine sliding paths in the rock. Repeating this calculation results in a distribution of possible sliding paths including the probability that no path will occur. These results can then be incorporated into a probability analysis.

56. A computer program for calculating the distribution of possible stepped paths is included in Appendix A. The step path option can be used independently or in conjunction with a probabilistic plane shear analysis provided by the

program.

57. Some workers define a "coefficient of continuity" of the joints,  $k$ , the proportion of joint surfaces along a potential sliding plane (Fig 18) (5). The shear strength of the potential sliding surface is then calculated as the average shear strength of the joint surfaces and the intact rock weighted in proportion to the continuity of each. In practice, the procedure is questionable because the total shear strength is extremely sensitive to the proportion of intact rock along the sliding path. Also, it is unlikely that the mechanism of sliding is as simple as implied by this model.

58. Another approach is to define the distributions of orientations and lengths of relevant joint sets (2). In the simplest case of plane shear, where movement is controlled by a single set of joints, sliding is assumed to occur when a joint that is continuous from toe to crest dips at an angle greater than the critical dip. By dividing the slope into a number of discrete elements the probability of instability for each section can be calculated (Fig 19)

59. If the probability of instability is for the full height of the slope, it is a function of the distribution of joint lengths. The theory of extreme values may be used to predict the probability of a discontinuity exceeding the length required to result in sliding within a given sector (7). This probability decreases as the required length (which is proportional to slope height) increases, hence the probability of instability will usually decrease with increasing height.

#### Computer Analysis

60. The Monte Carlo approach provides a practical method for determining the probability of sliding if all input parameters are subject to significant dispersion and are independent variables. The computer program in Appendix A is developed for this analysis.



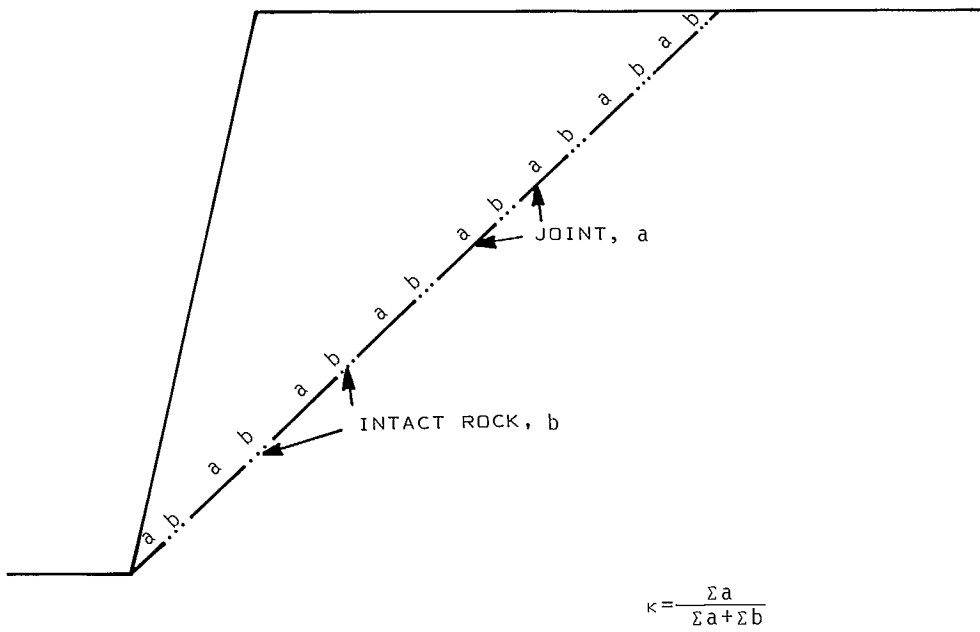


Fig 18 - Definition of coefficient of continuity.

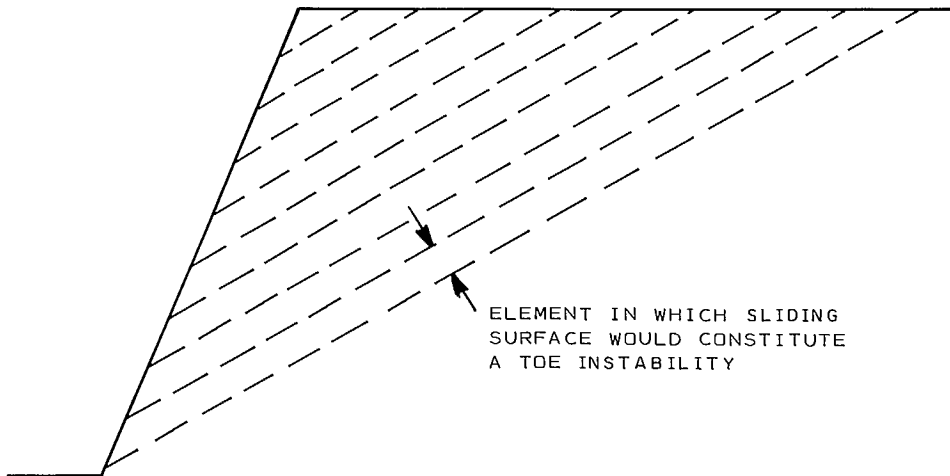


Fig 19 - Dividing a slope into elements.

## TWO-BLOCK PLANE SHEAR SLIDING

### Stereographic Solution

61. The forces acting in the general two-block problem are shown in Fig 20 (8). A stereographic analysis is a convenient way of determining whether or not a two-block configuration will be stable (9, 10). The shear strength envelope can be accounted for by use of the secant angle of friction.

62. Example 7. Determine whether the two-block system of Fig 21 will be stable. For convenience, consider the slope to strike east-west. Consider a unit width of the slope.

63. By application of the sine rule or from a scale drawing, the volumes of the active and passive blocks are  $324 \text{ ft}^3$  ( $9 \text{ m}^3$ ) and  $642 \text{ ft}^3$ , ( $18 \text{ m}^3$ ) respectively. The weights of the blocks are:

$$WA = 51,840 \text{ lbs (23,560 kg)}$$

$$WP = 102,720 \text{ lbs (46,690 kg)}$$

64. The normals and friction circles to planes (1) and (2) are plotted on a spherical projection as shown in Fig 22. The two weight vectors WP and WA plot at the center of the projection because

they are vertical.

65. The weight vectors plot inside the friction circle of the passive block, indicating this block would be stable without the action of the active block, and outside the friction circle of the active block by  $15^\circ$ , indicating this block would slide without the restraining effect of the passive block. To make the active wedge stable, WA must be rotated  $15^\circ$  or more by a transfer of force  $R_3$  from the passive block across the common plane.

66. A force polygon, as shown in Fig 23, consists of two superimposed triangles with a common vector  $R_3$  which is the force transmitted across plane (3). WA is drawn first, then the direction of  $R_3$ . Limiting equilibrium of the active block occurs if the resultant of these forces is rotated  $15^\circ$  from WA, which defines the magnitude of  $R_3$  at limiting equilibrium of the active block. Any external forces on the block, such as can be produced by water pressure, slope reinforcement or earthquake loading, can be accounted for by adding these quantities to the weight vector before the force polygon is closed using the known orientations of the forces  $R_1$ , and  $R_3$ , as is shown

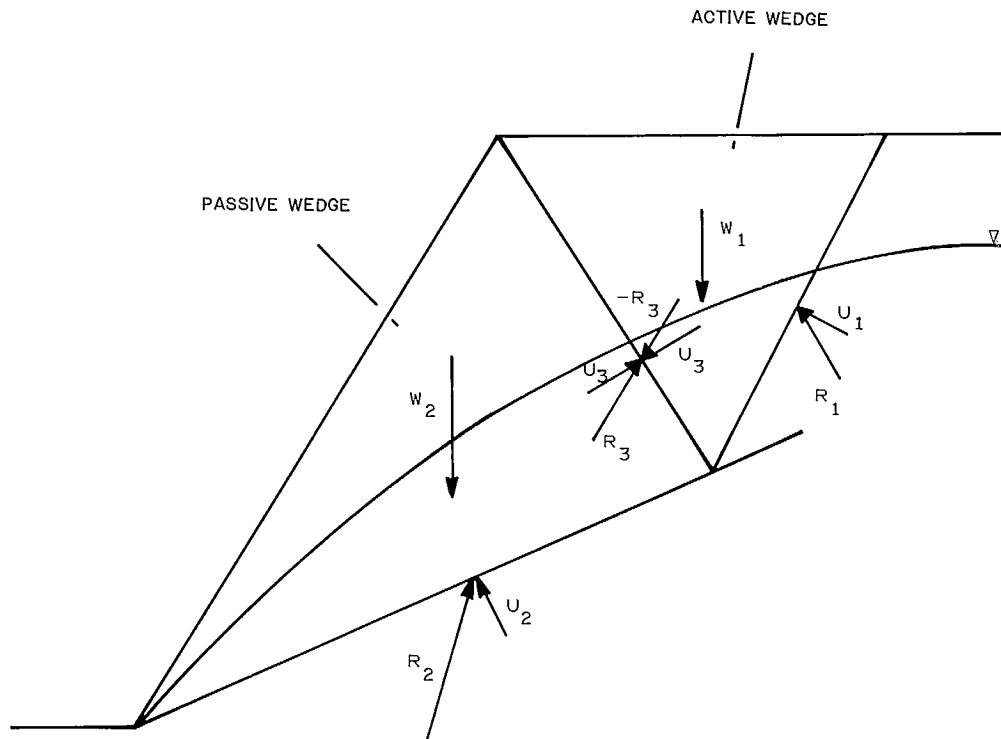


Fig 20 - Forces acting in the two-block problem at limiting equilibrium.

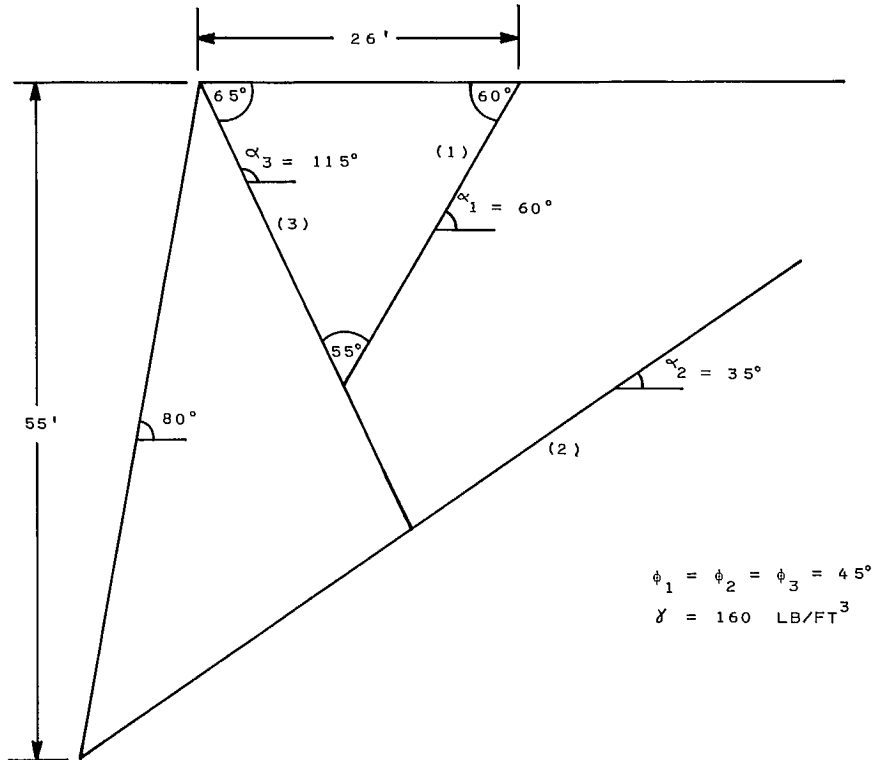


Fig 21 - Configuration for sample two-block problem.

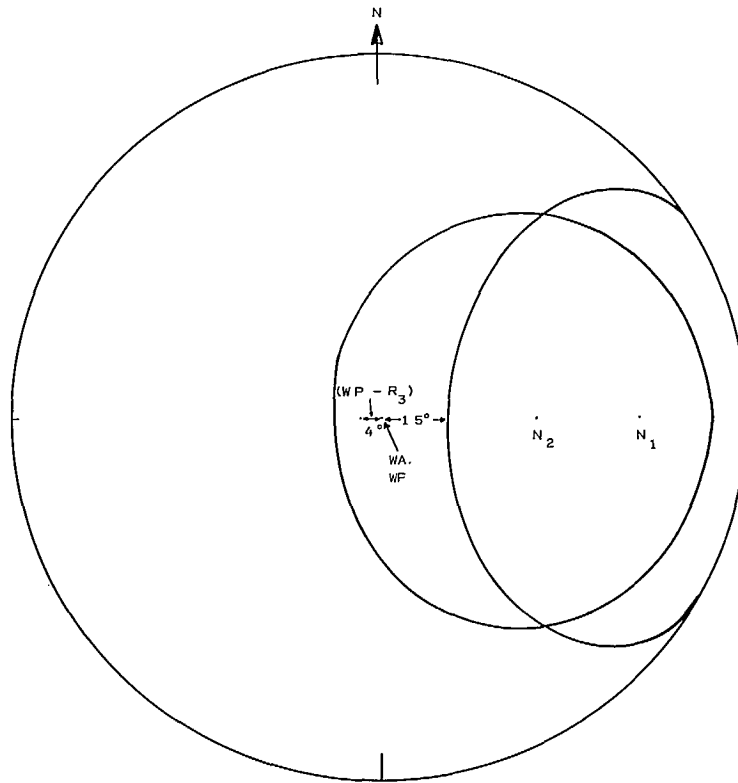


Fig 22 - Two-block analysis using spherical projection.

in Fig 23.

67. The force acting on the passive block due to its weight and the action of the active block is given by  $R_2 = WP - R_3$ . The angle from the vertical at which these forces act can be measured from the force diagram. In this case, the angle is  $4^\circ$ , determining the direction of  $R_2$ .

68. Returning to the spherical projection, the direction of the resultant force on the passive block can be plotted as shown. If this falls within the friction circle of  $N_2$ , as it does in this example, the system is stable. The closeness of this resultant to the friction circle gives a measure of how close the system is to sliding.

#### Critical Dip

69. Two-block sliding can be analyzed using a critical dip approach by considering the critical dip of the basal shear surface of the passive block. This analysis assumes the discontinuity orientations are deterministic. The construction of the force polygon is illustrated in the example

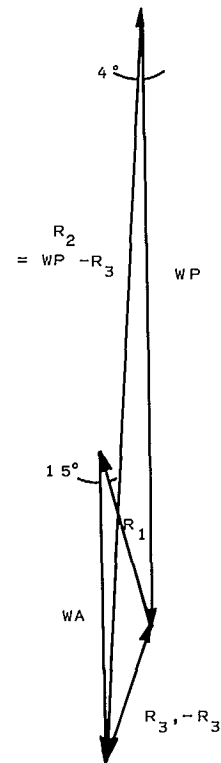


Fig 23 - Two-block analysis force polygon.

below (4).

70. Example 8. Determine the probability of two-block sliding in Fig 24 for a standard deviation of the dip of the shear plane of  $5^\circ$ . Consider a unit width of the slope. By application of the sine rule.

$$WA = 45,000 \text{ lbf (200 kN)}$$

$$WP = 115,500 \text{ lbf (514 kN)}$$

71. The force due to water pressure acting on each block is determined as shown in Fig 25.

72. The force polygon for the active wedge can be drawn for the limiting equilibrium condition by plotting the known magnitudes and directions of  $WA$  and  $UA$  and using the known directions ( $\phi$  degrees from the normal to the respective planes) of  $R_1$  and  $R_3$  to close the polygon, as shown in Fig 26.

73. The force polygon for the passive wedge can be drawn superimposed on that for the active block by recognizing that the force transmitted to

the passive block from the active block is equal and opposite to  $R_3$ , the force transmitted to the active block from the passive block. The whole system will be at the condition of limiting equilibrium when the full shear strength of the basal plane is mobilized, at which point the normal to this plane will make an angle  $\phi$  ( $45^\circ$ ) with the resultant of the normal and shear forces acting on this plane ( $R_2$ ). The critical dip  $\beta_c$ , is the dip of the basal shear plane at this limiting condition, which in this case is  $37^\circ$ .

74. The probability of instability is therefore the probability that the basal shear plane will dip more steeply than  $37^\circ$ , which equals 8 per cent.

#### Computer Analysis

75. A computer program to analyze two-block sliding is described in Appendix B. Cohesive forces on the shear planes, water forces, and external forces can all be accounted for in the

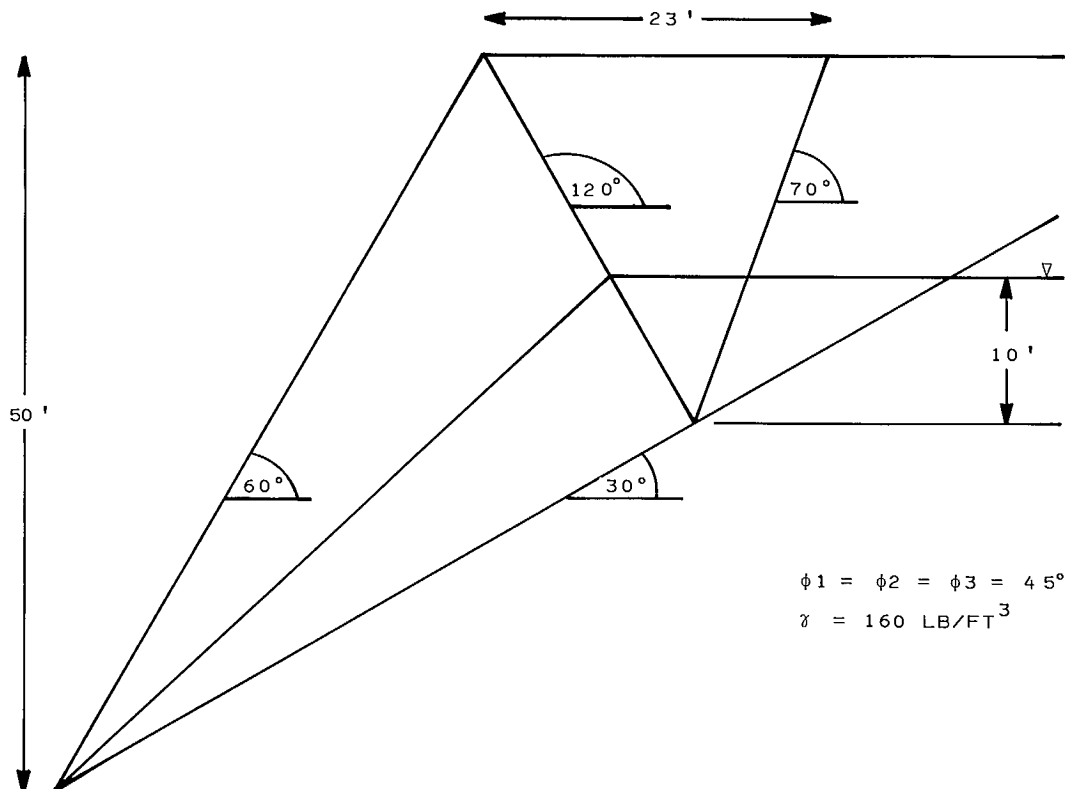
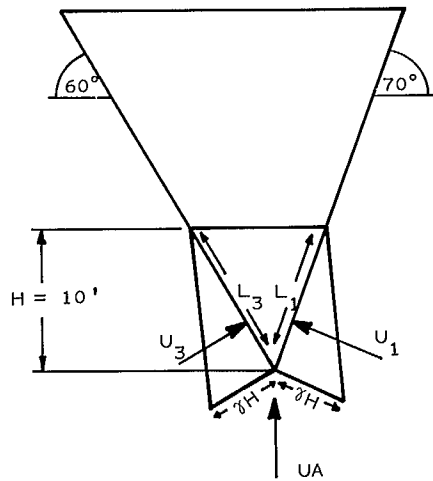


Fig 24 - Two-block analysis using critical dip.

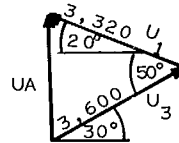
ACTIVE BLOCK :



$$U_1 = \frac{\gamma H^2}{2 \sin 70^\circ} = 3,320 \text{ LB}$$

$$U_3 = \frac{\gamma H^2}{2 \sin 60^\circ} = 3,600 \text{ LB}$$

$$\overline{UA} = \overline{U_1} + \overline{U_3}$$

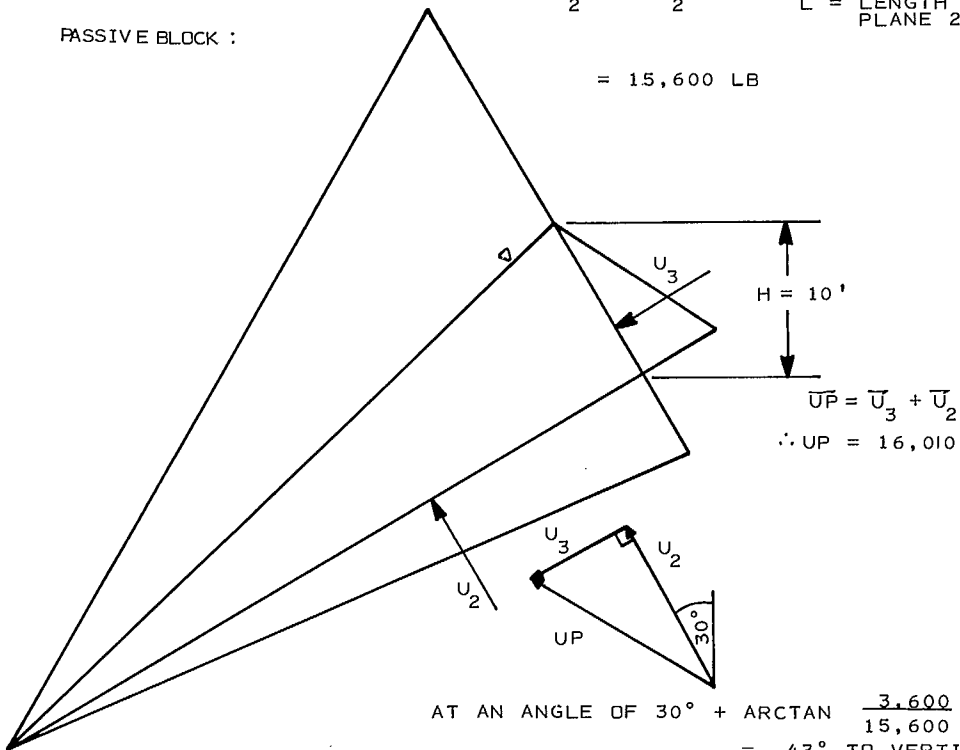


$$\therefore UA = 2,940 \text{ LB VERTICAL}$$

PASSIVE BLOCK :

$$U_2 = \frac{\gamma H \times L}{2} \quad L = \text{LENGTH OF PLANE 2}$$

$$= 15,600 \text{ LB}$$



$$\overline{UP} = \overline{U_2} + \overline{U_3}$$

$$\therefore UP = 16,010$$

$$\text{AT AN ANGLE OF } 30^\circ + \text{ARCTAN } \frac{3,600}{15,600} = 43^\circ \text{ TO VERTICAL}$$

Fig 25 - Calculation of water forces in two-block sliding.

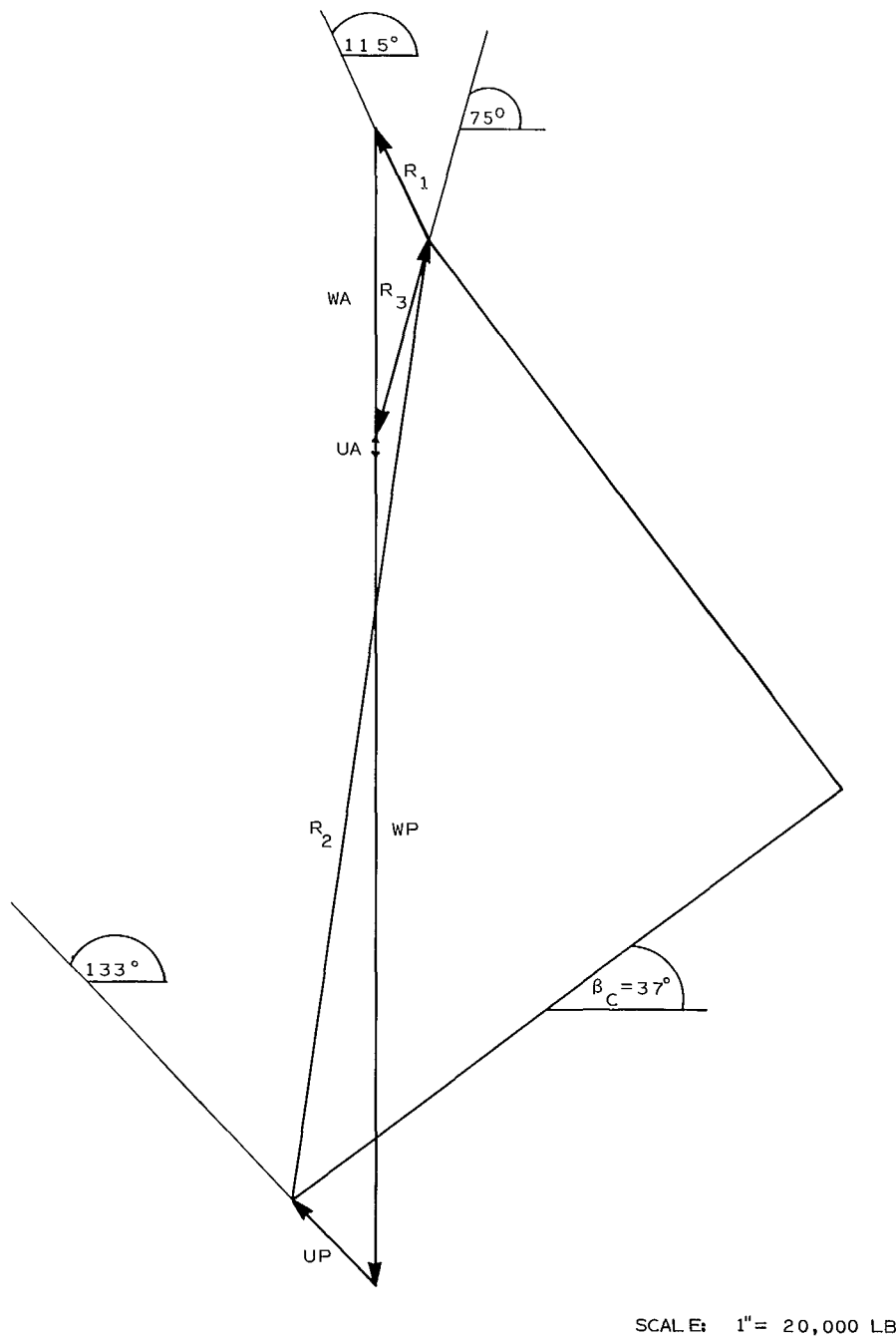


Fig 26 - Force polygon for critical dip two-block analysis.

analysis. The stability of the system can be expressed in terms of factor of safety. A sensitivity analysis is included, which allows all input parameters to be varied with automatic plotting of the results.

76. A Monte Carlo overlay option provides a

means for determining the probability of instability and enables all input parameters to be considered as stochastic variables.

77. A sample problem is included in the documentation of the program.

### 3-D-WEDGE SLIDING

#### Spherical Projection

78. The 3-d-wedge slide, as illustrated in Fig 27, is a common mechanism of rock slope instability. It is particularly common on benches. The problem can be analyzed using spherical projection techniques.

79. When the strength of the discontinuities is entirely frictional and there are no external forces, the problem can be analyzed graphically. The introduction of water pressure or other external forces requires the use of calculations to determine the orientation of the resultant force acting on the wedge. The construction of a zone of orientations for the resultant force for which the wedge will remain stable is illustrated below.

80. Example 9. Determine the factor of safety against sliding down the line of intersection of the wedge formed by joints at the following orientations.

	Plane A	Plane B
Dip Direction	40°	140°
Dip	50	60

81. The effective friction angle is 25° on plane A and 32° on plane B. The normals to the shear planes,  $N_A$  and  $N_B$ , are plotted in Fig 28, and friction circles of radius  $\phi$  (25° and 32°) are drawn around these normals.

82. The orientation of the line of intersection of the wedge,  $I_{AB}$ , is determined by the intersection of the projections of the discontinuity plane. As sliding is in the direction of the line of intersection, this is also the orientation of the shear forces on each plane,  $S_A$  and  $S_B$ .

83. The direction of the reaction on each plane at the limiting equilibrium condition,  $R_A$  and  $R_B$ , lies in the plane defined by the normal and by the shear forces. The reaction is at an angle of  $\phi$  degrees from the normal, the intersection of the friction circle and the plane of the normal and shear force.

84. The resultant of the reactions on both shear surfaces lies in the plane of these reactions. This plane is defined by the great circle which passes through the orientations of these reactions. Note that the two great circles which fulfill these conditions define the limiting equilibrium conditions for sliding down and up the line of intersection. Within the limits of these great circles and the friction circles is the stable zone. The wedge will remain stable as long as the resultant force acting on the wedge falls within this zone.

85. The resultant of the normal forces,  $N_A$  and  $N_B$ , acting on each shear plane lies in the plane defined by the two normal forces. This is represented by the great circle containing both these points.



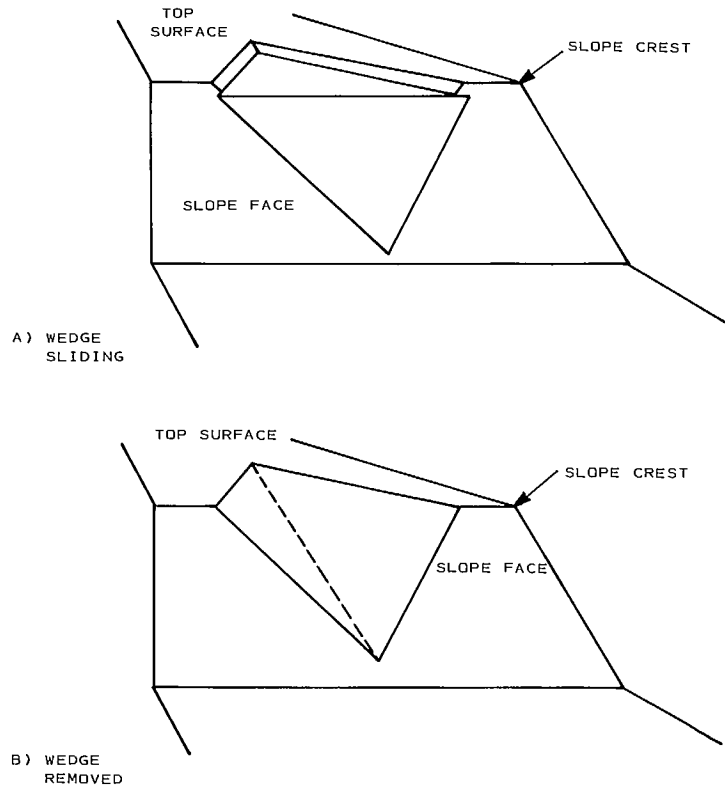


Fig 27 - 3-d-wedge sliding mode.

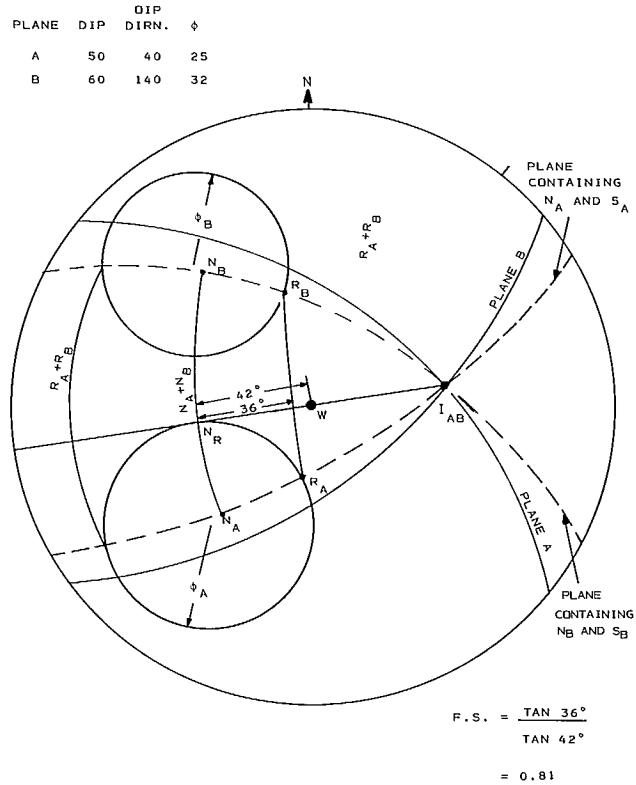


Fig 28 - Stereographic wedge analysis.

86. The direction of the resultant driving force, acting on the wedge can be plotted directly on the net. If the wedge is acted on only by gravity this direction is vertical and so plots in the center of the net. Otherwise, the direction can be determined by construction of the force polygon. If this resultant force lies within the stable zone, the wedge will be stable.

87. To determine the factor of safety against sliding, the great circle containing both the resultant force,  $W$ , acting on the wedge and the resultant shear force, which is defined by the intersection point  $I_{AB}$ , is drawn. The intersection of this great circle with the great circles through the normals and through the reactions defines the positions of the resultants of these normals and reactions,  $N_R$  and  $R_R$ . Measuring along this great circle gives the angle of  $36^\circ$  between the resultant normal,  $N_R$ , and the resultant reaction,  $R_R$ . The angle between  $N_R$  and  $W$  is  $42^\circ$ . The factor of safety can then be defined as the ratio of the resultant shear strength,  $N_R \tan 36^\circ$ , to the resultant shear force,  $R_R \tan 42^\circ$ :

$$FS = \frac{\tan 36^\circ}{\tan 42^\circ} = 0.81$$

88. Charts are available which can be used to assess the stability of rock wedges for which there is no cohesion or external forces (11). Under these conditions and for a given friction angle, the factor of safety is a function only of the dips and dip directions of the shear planes. These charts are convenient to use for simple wedge problems.

89. It is possible to recognize the uncertainty in the orientations of the shear planes in determining with a specified confidence whether a given wedge will slide. A close approximation is given simply by shrinking the friction circle about the normals to the shear planes by an amount equal to the uncertainty associated with orientation of the shear planes at the chosen confidence level. Construction of the stable zone is then carried out in the usual manner.

90. If the resultant force acting on the wedge falls within the stable zone the wedge will be

stable with a certainty greater than the specified confidence level. This certainty will equal the specified confidence level when the resultant falls on the boundary of the stable zone and will be less than the specified confidence level if the resultant falls outside the stable zone.

#### Critical Dip

91. The critical dip approach, can also be modified to determine the probability of a 3-d-wedge slide assuming both shear surfaces to have the same angle of friction (2). In this case, the critical dip refers to the dip of the line of intersection of the wedge and is as follows:

$$\tan \beta_C = K \tan (\phi - \alpha) \quad \text{eq 10}$$

$$K = \frac{\sin \theta_A + \sin \theta_B}{\sin (\theta_A + \theta_B)} \quad \text{eq 11}$$

where  $\alpha$  is the angle that the resultant force on the wedge,  $R_f$ , makes with the vertical,  $\theta_A$  and  $\theta_B$  are the apparent dips of the shear surfaces in the plane normal to the line of intersection of the wedge.

92. The orientation of the line of intersection is a function of the orientations of both shear planes. Hence its variation is a function of the variations of the orientations of the shear planes. A separate calculation is required to determine this distribution.

#### Computer Analysis

93. A computer program, which performs a limiting equilibrium analysis of a slope containing a 3-d-wedge, is described in Appendix C. It uses different shear strengths on each of the potential sliding surfaces, a tension crack, inclination of the upper wedge surface, a range of groundwater pressures and an external force (11). The factor of safety is determined, and any input parameter may be varied to determine sensitivity to changes in that parameter.

94. A Monte Carlo overlay is used to determine the probability of sliding. A sample problem is included in the documentation of the program.

## SLIDING ALONG BI-LINEAR AND OTHER SURFACES

95. Historically the commonest form of sliding amenable to analysis has been the circular slip surface. The sliding mass tends to rotate about the center of the circle defining the slip surface. Supplement 5-2 deals with this analysis.

96. The Spencer-Wright program can cope with both circular, non-circular and bi-linear surfaces (12, 13). The program included in Appendix D has options for sensitivity and probabilistic analyses. The input parameters may be described by one of five different statistical distributions. A full description of the program with an example is included in the appendix.

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## APPENDIX A

### PROGRAM DOCUMENTATION OF PLAFAM

(plane failure analysis including Monte Carlo simulation)





## ABSTRACT

This program performs a limiting equilibrium analysis of the stability of a rock slope in which there are discontinuities dipping in the same direction as the slope face and striking almost parallel to the face. The cases of a single throughgoing discontinuity or a stepped sliding surface can be analyzed. A factor of safety is calculated as the ratio of the resisting forces to the driving forces acting along the

sliding surface. Input parameters can be varied individually to determine the sensitivity of factor of safety to such variations, and the results can be plotted automatically. The probability of instability is determined by a Monte Carlo overlay; this can be used in conjunction with the sensitivity options to generate a plot of probability of instability against the parameter being varied.

## PROGRAM IDENTIFICATION

Program Title: Plane Shear and Step Path Instability Analysis for a Rock Slope

Program Code Name: PLAFAM

Writer: H-S. Kim, G. Major, A. Bealer

Organization: Dames & Moore for Canada Centre for Mineral and Energy Technology

Date: October 1975

Updates: Histogram data input added December 1976.

Source Language: FORTRAN IV

Availability: Mining Research Laboratories, CANMET, Department of Energy, Mines and Resources, 555 Booth St., Ottawa, K1A 0G1, Canada. Fortran source deck and listing on magnetic tape will be supplied at nominal cost.

## ENGINEERING DOCUMENTATION

### Introduction

1. Program PLAFAM performs a limit equilibrium analysis for the case of a rock slope which may slide along a single discontinuity plane, or along a stepped path. It should therefore be used only for cases in which the controlling discontinuities strike nearly parallel to the slope face. The program allows for the inclusion of a vertical tension crack which may be located behind the slope crest or in the slope face, the effect of an externally applied load as may result from reinforcement or a surcharge, and a pseudo-static representation of earthquake loading. The step path option simulates a sliding path along two sets of joints, both of which are assumed to strike parallel to the slope face but to dip at different angles.

2. The step path option can be used independently or in combination with the slope stability analysis. A piezometric line is defined by linear segments which can represent any shaped surface as accurately as may be required. A kinematic check ensures that all geometries analyzed in deterministic or probabilistic cases are valid instances of plane instability, by comparing the dip of the sliding surface with the dip of the slope face.

3. The options available for performing automatic sensitivity and probability analyses are

particularly useful for analysis and design. The Monte Carlo overlay used in all probabilistic analyses has been documented separately in Appendix E.

### Simple plane shear analysis

4. The input information required to define the sliding volume is that which is the most readily obtainable from routine field investigations. For the simple case of sliding along a single plane this consists of the slope height, the inclinations of the face and sliding plane, and the distance from the slope crest to the tension crack (Fig A-1). All other lengths are calculated with the program and are printed as output on each run.

5. Water pressures on the sliding surface are calculated from the piezometric line as:

$$u = \gamma_w h$$

where:  $u$  = pressure,

$\gamma_w$  = density of water, and

$h$  = height of the piezometric line above the sliding surface.

Points on the piezometric line are specified by the coordinate system which takes the toe of the

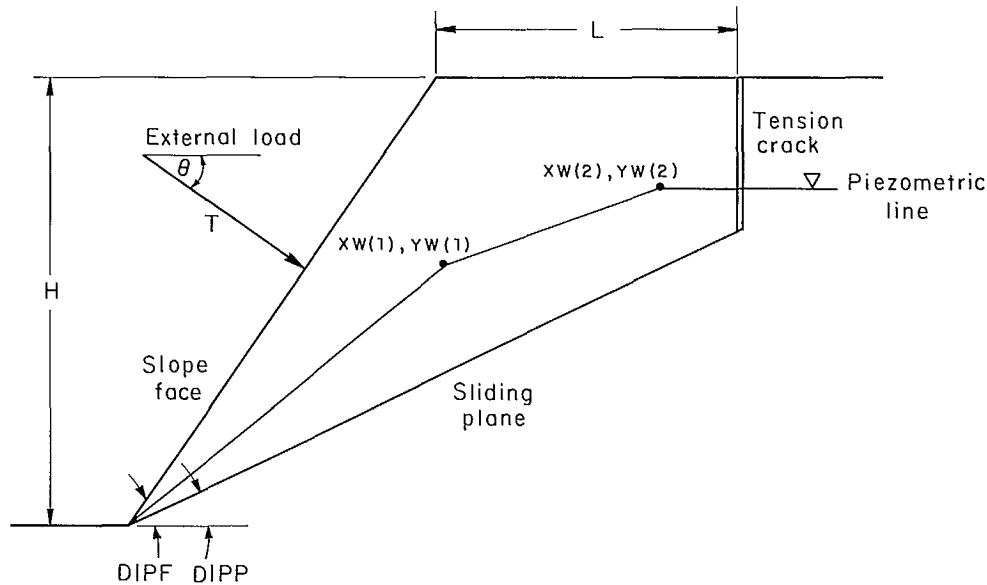


Fig A-1 - Parameters of plane sliding.

slope as the origin. The total uplift force is calculated by summing the products of the water pressures and the areas over which they act.

6. In the case where water is present in the tension crack, the piezometric line corresponds to the phreatic surface where it crosses the tension crack. The horizontal force exerted by the water in the tension crack is calculated as:

$$V = 0.5 \gamma_w Z_w^2$$

where:  $V$  = horizontal force, and

$Z_w$  = height of water in the tension crack.

7. The piezometric line is preferred because of the difficulty in calculating water pressures from a phreatic surface which is not horizontal. Where water measurements are made in open boreholes, the piezometric line should be estimated from the standing water level.

8. An externally applied load is specified in magnitude,  $T$ , and dip,  $\theta$ . The dip will be greater than  $90^\circ$  if it is in the same dip direction as the slope face and negative in value if it has a component directed upwards.

9. Any force due to earthquake acceleration,

$E$ , is assumed to act horizontally. It is modelled by an equivalent static force resolved into forces normal to and parallel to the sliding plane. The factor of safety is then calculated as the sum of forces tending to induce sliding, divided by the sum of the forces tending to prevent sliding.

10. In the case of a probabilistic analysis, all input variables are considered to be independent. If desired, the value of points on the piezometric line can be sampled in the  $y$ -direction, but all must be sampled using the same type of distribution.

11. The toe of the slope is always considered to be the first point on the piezometric line and should not be specified as input. This point is not sampled even if the others are sampled. The dip of the slope face is always considered deterministic. If the height of the slope,  $H$ , is varied in a sensitivity analysis, the location of the piezometric line ( $XW$  and  $YW$ ) and tension crack ( $L$ ) are scaled so that the geometry of the system remains the same. No scaling is performed for variations in any other parameter during sensitivity analyses. The sensitivity analysis option should not be used if these scaling assumptions are inappropriate.

### Step Path Option

12. When two distinct joint sets lie nearly parallel to a slope face, there is the possibility of a stepped sliding path being formed as shown in Fig A-2. Stepped path stability analysis involves the following:

- a. simulation of the two joint systems present in the rock mass in terms of their distribution of orientation, length, and spacing to calculate the possible stepped failure paths and their continuity, and
- b. analysis of the stability of the rock slope using the defined stepped failure paths.

13. Step Path is the sequence of joints which have been sampled by the simulation technique used to define possible paths, a typical one is shown in Fig A-2. Consecutive joints in the path do not necessarily intersect.

14. Beta Angle ( $\beta$ ) is the angle defined by the plane from the bottom of the step path, or toe of the slope, to the top surface of the slope such that the areas defined by the step path above and below the plane are equal. The plane is referred to as the beta plane and represents a mean sliding path. The mean beta angle is calculated from a series of step path simulations which have resulted in continuous step paths.

15. Major Joints ( $\alpha$  Joints) are those which dip out of the slope at the lowest angle. Any

sliding is assumed to take place along these joints. Total Major Joint Length (TMJL) is the sum of the lengths of all major joints, including the lengths of any rock bridges which may be present in the step path parallel to the major joint direction. It is determined by the progressive summation of the joint lengths during step path simulation.

16. Cross Joints ( $\psi$  Joints) are those which provide the connection of the step path between major points. They may dip to either side of the vertical.

17. Termination Point is the intersection of the last step in the defined path with the tension crack, or with the top surface of the slope, or with a vertical line at some horizontal distance from the toe as specified by the user.

18. Overlap refers to that length of a joint on the path which constitutes a part of the path, as in Fig A-3.

19. Rock Bridge is the intact rock between the end of one joint and the next sampled joint. According to the failure criterion for the bridges, this bridge may or may not be considered to fail. When the bridge is parallel to a major joint it can fail only in shear; if parallel to a cross joint it can fail only in tension.

20. Continuous Step Path is one along which any rock bridges are assumed to fail by the

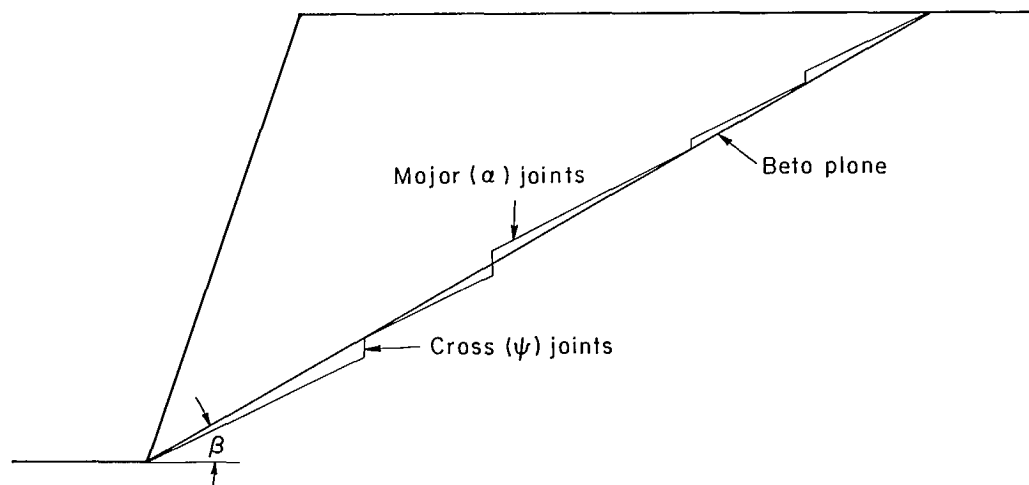


Fig A-2 - Typical stepped sliding path.

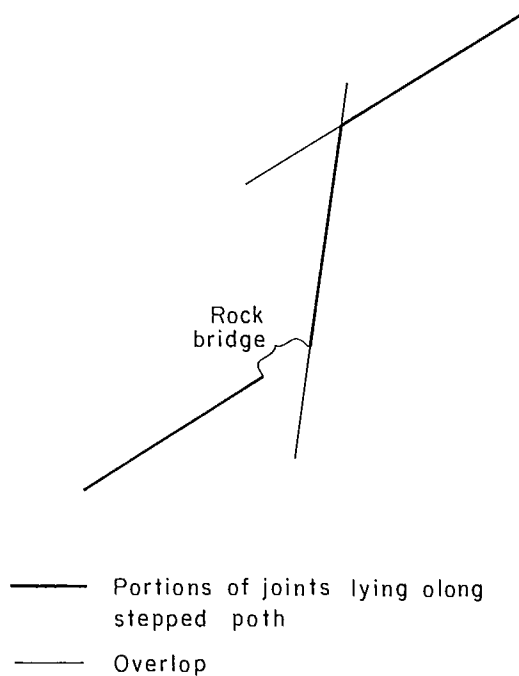


Fig A-3 - Definition of overlap and rock bridge.

propagation of the joints during the generation of the step path.

21. In a rock mass which contains major and cross joints with a potential stepped sliding path, the absolute location of individual joints will not be known. A model to simulate potential stepped sliding surfaces based on the lengths, spacings and orientations of the joints forming the step path has been developed by Call (A-1). This results in an estimate of the distribution of possible step paths to provide suitable input for a stability analysis. In this model, cases in which no continuous path is found are rejected and joint sampling terminated at the first rock bridge which will not fail according to the selected

failure criteria. Data on rejected cases is not used.

22. This model has been modified so that cases in which there is not a continuous path are not rejected. Instead, the simulation of the step path is continued until it reaches a termination point. The cases with no continuous path are counted and the total length of rock bridges determined, to calculate the percentage of rock bridges along both the major and cross joint sections of the path, ie, the joint continuity factors. This factor excludes those bridges which have failed during the simulation.

23. The step path consists of alternating major joints and cross joints. These joints are

sampled using the specified distributions of length, spacing, orientation and overlap. Rules for defining the sliding path are as follows.

- a. Rock bridges less than a given value  $\lambda$  will fail due to shear stress, while those greater than  $\lambda$  will not fail. It has been suggested that  $\lambda \approx 0.1m$ , but no such default value is used in the program. Instead, the user is expected to specify a value for  $\lambda$ .
- b. Any cross joint will propagate, due to the induced tensile stress, to the first major joint it intersects but not beyond. The distance over which a cross joint will propagate can be specified by the user if required.
- c. The flattest step path will be followed; that is, the cross joint which intersects a major joint the furthest along the major joint is the one which will form the step path. Sampling of cross joints for a given major joint continues until a cross joint is sampled at some distance beyond the major joint where the rock bridge will not fail. The previous cross joint is then used to define the step path.
- d. The overlap of fractures is represented by a uniform distribution. Hence, a sampled joint

is equally likely to cross the previous step or its projection at any point along the length of the sampled joint. This is the case for both major and cross joints. The distribution of overlap can be specified as input if required.

- e. In sampling cross joints for all but the first major joint, any cross joint which does not lie further along the step path than the last sampled cross joint or the previous major joint, is rejected if the cross joint crosses the projection of the previous major joint as shown in Fig A-4.

24. Enabling the user to specify the failure criteria for rock bridges and the calculation of joint continuity factors gives him sufficient flexibility to incorporate the intact rock strength into the sliding path criterion for the slope to whatever extent is considered justified.

25. The following assumption enables additional valuable information on joint continuity to be obtained from the model. Both continuous and discontinuous step paths provide valuable information concerning possible instability. The paths which are not continuous give a measure of whether a

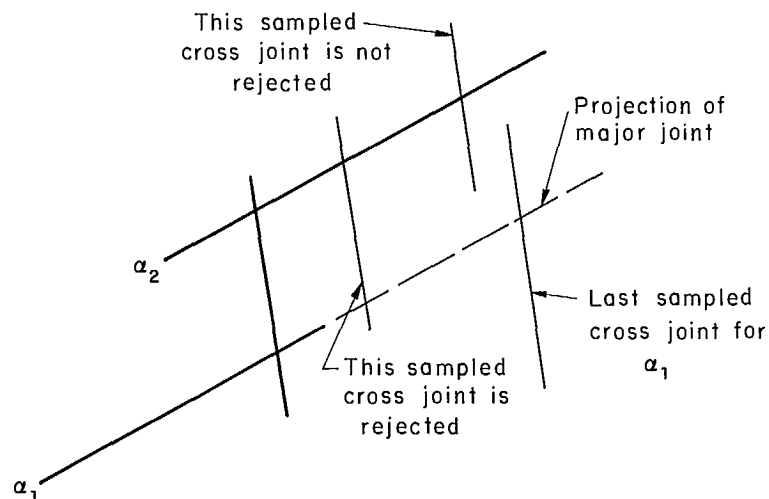


Fig A-4 - Rejection criteria for cross-joints.

sliding path will form at all. Paths are discontinuous if the first sampled cross joint for a given major joint does not cross the major joint.

26. The number of step paths which are not continuous could be used quantitatively to reduce the probability of instability calculated on the assumption that a path will always be formed. This would, however, require a high degree of confidence in the correctness of the input data, especially if the number of "no path" cases is large. The judicious use of the option which enables the inclusion of the intact rock strength in the calculation of the factor of safety is a more suitable alternative.

27. The distribution of the orientations of the completed sliding paths provides a parameter which can be input directly into a slope stability analysis. Used in conjunction with a deterministic stability analysis, the mean beta angle calculated is assumed to be the mean orientation of the stepped surface. When the step path orientation is used in conjunction with a probabilistic slope stability analysis, the mean and standard deviation of the beta angles are used to define a normal distribution, truncated at the highest and lowest values sampled, whence beta angles are sampled for use in the analysis. The user should be aware that this procedure may be inappropriate if the distribution of the beta angles of the step paths departs significantly from normal.

28. When the stepped path option is used, an independent package of subroutines is used to simulate a series of step paths along the major and cross joints. From the simulations the

natively, it can be used either in conjunction with a deterministic or a probabilistic slope stability analysis.

30. For a deterministic analysis, the mean values of the variables relevant to the stability analysis are used to determine the factor of safety.

31. For the probabilistic analysis, the computed mean values and standard deviations of all relevant variables are used to resample these variables for each stability calculation in the Monte Carlo process. The following distributions are assumed for these variables:

- a. gaussian or truncated gaussian for the beta angle (BETA) and the total lengths of the joints (TMJL and TCJL); gaussian is used if the overall range over the sampled values on each of these variables is within six standard deviations.
- b. exponential for continuities (CONTMJ and CONTCJ); if all sampled values are the same, these variables are taken to be deterministic.

32. Stability analysis of sliding along a stepped surface can be carried out using a method similar to that described for the simple plane shear case.

33. The idealized step path situation in which all major joints are parallel has been considered by Jennings (A-2) and Jaeger (A-3).

34. By assuming that shear strength parameters are the same throughout the slope and that the effective normal stresses across each joint set remain constant (ie, the average effective stress), the factor of safety against sliding can be written:

$$FS = \frac{\{W[\cos\alpha] - U[\cos(\beta - \alpha)] - (EW + V)[\sin\alpha] + T[\sin(\theta + \alpha)]\}\tan\phi_a + L_{MJ}C_a}{W[\sin\alpha] + U[\sin(\beta - \alpha)] + (EW + V)[\cos\alpha] - T[\cos(\theta + \alpha)]} \quad \text{eq 1}$$

sampled distributions of various quantities characterizing the step path, eg, the average step path angle which is termed the  $\beta$  angle, the lengths of major and cross joints along the step path, joint continuities, are calculated and printed out.

29. The step path option can be used independently of the stability analysis options. Alter-

where: W = weight of the mass bounded by the slope face, top surface, the average sliding plane and the tension crack if present,

[ ] = average value of the quantity within the parenthesis,

$\alpha$  = dip of major joints,

$\beta$  = beta angle,

U = total uplift force due to water

pressure acting on the average sliding plane,

$E$  = earthquake coefficient,

$V$  = hydrostatic force due to water in the tension crack,

$T$  = magnitude of externally applied force,

$\theta$  = dip of externally applied force,

$\phi_a$  = average friction angle of the major joints,

$L_{MJ}$  = total length of the major joints along the step path, and

$C_a$  = cohesive strength of major joints.

35. The factor of safety expression is similar to that used for the case of simple sliding along a single plane.

36. Equation 1 can be extended to account for the shear and tensile strengths of the rock bridges if their inclusion is justified. The factor of safety expression is modified as follows:

a. a term,  $t_a$ , must be introduced to account for the tensile strengths of the rock bridges on the cross joints. This is given as:

$$t_a = L_{CJ}[1 - K_{CJ}]$$

where:  $L_{CJ}$  = total length of the cross joints,

$K_{CJ}$  = joint continuity factor for the cross joints, and

$t$  = tensile strength of the rock.

Since this increases the resisting force, this force is added to the numerator of the factor of safety expression, eq 1.

b.  $\tan \phi_a$  and  $C_a$  become a weighted friction angle and cohesion, to account for the frictional shear strength and cohesion of both the major joints and the intact rock bridges. Hence:

$$\tan \phi_a = [K_{MJ}] \tan \phi_J + [1 - K_{MJ}] \tan \phi_M$$

$$\text{and } C_a = [K_{MJ}] C_J + [1 - K_{MJ}] C_M$$

where:  $K_{MJ}$  = joint continuity factor for the major joint sets ie, the fraction of the path in the direction of

the major joints which lies along joints rather than through intact rock,

$\phi_J$  = friction angle of the major joints,

$\phi_M$  = friction angle of the intact rock,

$C_J$  = cohesive strength of the major joints, and

$C_M$  = cohesive strength of the intact rock.

37. As sliding is assumed to occur only along the major joint set, the shear resistance and driving forces are summed in the average direction of the major joints.

38. The weight of the sliding mass and water uplift forces are calculated using the beta plane. The definition chosen for the beta angle ensures that no error is introduced into these calculations. The weight of the sliding mass is calculated from the coordinates of its corners.

39. The total uplift force is perpendicular to the  $\beta$  plane. This force is therefore resolved into two components, one perpendicular to the major joints, considered as reducing the normal stress on these surfaces, and one parallel to the major joints which is added to the driving forces acting in the direction of movement.

40. In the analysis for a stepped surface, the user can either specify the necessary data concerning the step path directly or use the step path simulation option to compute the required values. Data specified directly could be derived from previous simulations. The sensitivity analysis option should not be used if step path simulation is used, since this would result in the regeneration of the same step paths for each new stability analysis.

41. When rock bridges are introduced into the stability analysis, the stability will be sensitive to their lengths and this, in turn, is related to the continuity factor. In the step path simulation program, the joint continuity factors are calculated by considering as joints any rock bridges which are found to fail during the simulation of the step path. Hence, the intact strength of these bridges is not considered to provide



additional restraining force. The length of rock bridges which can fail during step path simulation can be specified by the user as BRIDGEM and BRIDGECE. Details of the criteria used in step path simulation are given below. If desired, all intact strengths can be included in the stability calculation by setting to zero the lengths of bridges which will fail in shear or tension in the step path simulation. Alternatively, the shear and tensile strength of the intact rock can be ignored by setting these strength values to zero. In view of the sensitivity of stability calculations to the inclusion of intact rock strength, it is suggested that full intact strength not be included unless there is strong justification.

42. In a probabilistic analysis all stochastic variables are assumed to be independent. They can be defined to have any of the following distributions:

- a. normal or gaussian,
- b. triangular,
- c. uniform or flat,
- d. truncated gaussian,
- e. exponential, or
- f. histogram (input by user).

43. Sampling limits are specified for all distributions except the normal for which the sampling technique used results in a cutoff at six standard deviations on either side of the mean.

44. For the probability analysis, the factor of safety is stored, and the calculations are repeated a specified number of times using new sets of input data sampled by the Monte Carlo overlay. The distribution of the calculated factors of safety is plotted, and the mean, standard deviation, skewness and kurtosis of these values are determined.

45. Probability of sliding is determined as the probability of the factor of safety being less than that at the limiting equilibrium condition, using one or both of the following techniques:

- a. the normal distribution curve defined by the mean and standard deviation of the calculated factors of safety is assumed to be that of their population; the probability of instability is determined by evaluating the area under this normal distribution curve to the

left of the limiting equilibrium condition; using a distribution curve to represent the calculated results serves to smooth out the irregularities expected from a random sampling technique, especially where the sample size is small.

- b. a direct count of the factors of safety falling below the limiting equilibrium condition is made, from which the probability of instability is determined as the percentage of the total population which these values represent; in addition to its simplicity, this method has the advantage that no assumptions need be made concerning the distribution of factors of safety; for small sample sizes, up to 100 samples or so, the irregularities associated with the Monte Carlo technique tend to have an adverse effect on the consistency of this method of estimation; for larger samples the direct count gives a reliable estimate; a sample size of 200 should usually give satisfactory results using the direct count method.

46. Marked differences between these two estimates may indicate either that the distribution is not normal or that some input values are unacceptable. These inconsistencies must be explained and understood before the most reliable estimate can be determined. Any departure of the output distribution from normality will be reflected in the skewness and kurtosis. Their values give a useful indication as to the validity of assuming a normal distribution.

47. A kinematic test is included, to check whether the dip of the sliding surface is less than that of the slope face. When a kinematically impossible case occurs, the factor of safety has no meaning, and so the distribution of factors of safety in a probabilistic analysis also loses its significance. The probability then is determined only by a direct count with kinematically impossible cases being counted as safe.

#### Program Capabilities

48. The program will analyze cases of plane sliding which can be modelled satisfactorily in two dimensions. Any end restraint on the sliding mass is thus not considered, which gives a

conservative effect. The top surface is always assumed horizontal, and any tension crack is assumed to be vertical. Moment equilibrium is not considered.

49. The linear segmented piezometric line enables any water distribution to be easily modelled. Up to 18 segments can be used. The shear strength of the sliding surface is assumed to be composed of frictional and cohesive components according to the relationship:

$$\tau = C + \sigma \tan \phi$$

where:  $\tau$  = shear strength,

$C$  = cohesion,

$\sigma$  = effective normal stress, and

$\phi$  = friction angle.

50. The representation of earthquake loading is made by the application of an equivalent horizontal static force in the direction of potential movement of the mass.

51. Three separate cases are included in the program:

- a. no tension crack,
- b. tension crack present behind slope crest, and
- c. tension crack present on the slope face, in which case the distance from the slope crest is specified as negative.

#### Program Options

52. The program determines a factor of safety for a single plane or a stepped path. Options enable automatic repetition of this calculation for sensitivity analyses and determination of probability of sliding. The sensitivity option allows the variation of all input parameters in the stability analysis, except the piezometric line, over specified ranges containing up to 40 step intervals. The parameter values and corresponding safety factors are stored in arrays for later printout in tabular form or along the axis of a sensitivity plot.

53. For the probabilistic analysis, the factor of safety is calculated a specified number of times, using input values for stochastic variables chosen from defined distributions by the Monte

Carlo overlay. The distribution of these factors of safety is plotted together with the mean, standard deviation, skewness and kurtosis of the values. The sensitivity analysis option should not be used if the step path simulation option is used.

#### Printed Output

54. A description of the variable names used is printed, followed by a listing of the values of variables input and calculated within the program, including the factor of safety.

55. In the case of a sensitivity analysis, this information is printed for each change of input variable. A plot of the change in the factor of safety with variation of the input parameter is produced. There are no options in this printout.

56. When a probabilistic analysis is made, there are three printout options available:

MPRINT = 0 prints out all input data and gives a plot of the distribution of the calculated factors of safety. The mean, standard deviation, skewness and kurtosis of this distribution are printed, together with the probability of sliding determined both by direct count and by assuming that the factors of safety are normally distributed.

MPRINT = 1 gives the printout of option 0 plus a list of the calculated factors of safety.

MPRINT = 2 results in the output of option 1 plus a list of sampled values as well as various calculated values of the factor of safety.

57. When the step path option is used, a detailed output is available (IPRT = 3) which lists details of the simulation of each step path, statistical data concerning simulation of each beta angle and distributions of generated step paths. Printout options available for the step path analysis give the following results:

IPRT = 0 gives a summary print of the step path simulation results including plots of the distributions of important parameters.

IPRT = 1 gives additional data concerning each simulated step path.

IPRT = 2 results in the printout of option 1

plus details of each step in each step path simulated.

IPRT = 3 gives the printout of option 2 plus details of every cross joint sampled in the simulation of the step paths.

58. Data printed for every step along the step path for IPRT = 3 consists of the following:

SAMPLE = the number of the step path being generated; this will run sequentially from 1 to MSAMPL.

ISTEP = the number of the step for the step path defined by SAMPLE.

IST NO OF RANDOM SEQ = the starting number of the random number generator for the simulation of step ISTEP.

DIP = the sampled dip of step ISTEP.

LENGTH 1 = the length of joint ISTEP to the left of (for a major joint) or beneath (for a cross joint) the previously sampled joint.

LENGTH 2 = the length of joint ISTEP to the right of (for a major joint) or above (for a cross joint) the previously sampled joint.

STEP LEN = the length of joint ISTEP which forms part of the step path.

BRIDGE L = the length of intact rock at the end of joint ISTEP which lies along the step path.

J-CONT K = joint continuity factor for joint ISTEP.

X-COORD = X coordinate of the step at the end of step ISTEP.

Y-COORD = Y coordinate of the step path at the end of step ISTEP.

DCHECK = Distance from the last intersection of a cross joint and a major joint to the first non-intersecting cross joint.

NCRS = the number of joints sampled, either major or cross joints as appropriate, which cross - or the projections of which cross - step ISTEP.

CROSSINGS = the distances at which sampled joints or their projections cross step ISTEP measured from the point where step ISTEP-1 intersects step ISTEP. These values are printed sequentially across the page, starting on the same line on which CROSSINGS is printed.

59. Data printed for each step path simulated is then printed out as follows:

the manner of termination of the step path, for

example, ENDED BY Y-BOUND if the step path generation continued all the way to the specified top of the slope.

BETA = beta angle.

MAJOR JOINT L = total length of the major joints lying along step path.

MAJOR BRIDGE L = total length of intact rock along the step path which must be sheared along the direction of the major joints for instability to occur.

CROSS JOINT L = total length of cross joints lying along step path.

CROSS BRIDGE L = total length of intact rock along the step path which must fail in tension along the direction of the cross joints for instability to result.

MAJOR J-CONT K = joint continuity factor for the total length of step path which lies along the major joint direction.

CROSS J-CONT K = joint continuity factor for the total length of the step path which lies along the cross joint direction.

X-COORD = X coordinate of the final point on the step path.

Y-COORD = Y coordinate of the final point on the step path

VOLUME = sum of areas formed by the line joining the origin to the end of the step path and the portion of the step path lying below this line, minus the sum of such areas lying above this line.

NWALK = the total number of steps made in the "random walk" simulation of the step path.

M-GAPS = the number of intact rock bridges lying along the direction of the major joints.

% M-GAPS = the percentage of intact rock bridges lying along the direction of the major joints.

C-GAPS = the number of intact rock bridges lying along the direction of the cross joints.

% C-GAPS = the percentage of intact rock bridges lying along the step path in the direction of the cross joints.

NO M-CRS = total number of cross joint samples which cross or form part of the step path.

60. The data on the entire sample of generated step paths consists of a table of calculated values, the maximum and minimum calculated values,

a histogram plot of frequency distribution, and sample statistics for the beta angle, the total major and total cross joint lengths and continuities, and the volume.

### Other Outputs

61. There are none.

### Flow Charts

62. A simplified flow chart for program PLAFAM is attached as Fig A-5.

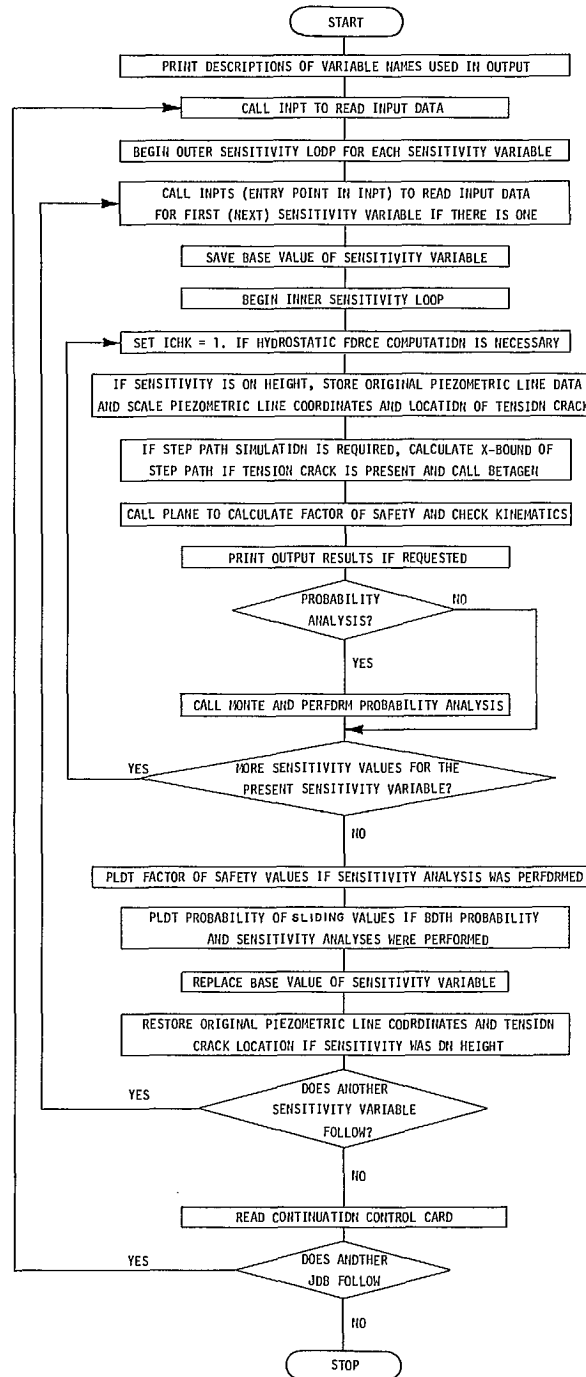


Fig A-5 - Flowchart of program PLAFAM.

## DATA INPUT

63. All input is on punched cards.

### A. Header card Format (A10,A3,A6,6A10)

Job number

User's initials

Date

Title (up to 60 characters)

### B. Control card Format (6F10.0)

CALCS - analysis control

0. = deterministic

1. = probabilistic

CODEA - tension crack control

0. = no tension crack

1. = tension crack

NW - number of points defining piezometric line  
(maximum 19)

CODEC - piezometric line sampling code

0. = deterministic

1. = probabilistic

NONSENS - number of sensitivity variables

NBETA - analysis control

0. = no step path analysis

1. = stability analysis using defined step  
path distributions

2. = step path simulation and stability  
analysis

3. = step simulation without stability  
analysis

### C. Slope definition cards (3 cards)

The numbers in parentheses are index numbers of the slope definition variables. Variables marked \* are used only for defining the step path.

Card C1 Format (8F10.0)

H(1) - slope height

L(2) - distance from crest to tension crack  
(ignore if CODEA = 0.)

DIP(3) - dip of slope face

DIPP(4) or DIPM\* - dip of sliding plane (DIPP)  
or dip of major joint (DIDM)

DIPC(5)\* - dip of cross joint

BETA(6)\* - dip of average plane of step path

CONTMJ(7)\* - major joint continuity (0. to 1.)

CONTCJ(8)\* - cross joint continuity (0. to 1.)

Card C2 Format (8F10.0)

TMJL(9)\* - total length of major joints

TCJL(10)\* - total length of cross joints

PHI(11) - friction angle of joint in degrees

C(12) - cohesion of joint

PHIROK(13)\* - friction angle of intact rock in  
degrees

CROCK(14)\* - shear strength of intact rock

TROK(15)\* - tensile strength of intact rock

DENR(16) - unit weight of rock

Card C3 Format (4F10.0)

DENW - unit weight of water

T - external force

THETA - dip of external force

ACCEL - earthquake coefficient

D. Piezometric line definition cards Format (8F10.0) NW pairs are required - see card B; skip D cards if NW = 0.

XW(1) - x-coordinate of point 1 on piezometric line

YW(1) - y-coordinate of point 1 on piezometric line

XW(2)

YW(2)

.

.

.

.

XW(19)

YW(19)

Up to 19 pairs allowed; use as many cards as required (5 cards needed for 19 pairs).

Note: starting point of piezometric line is always assumed by program to be the toe of the slope (point 0,0) and this point is therefore not input.

E. Probabilistic analysis control card Format (8F10.0)

NSAMPL - number of samples

MFIRST - first seed for random number generator

MPRT - print code

0. = input and results of statistical analysis printed

1. = as for 0. plus factor of safety table

2. = as for 1. plus detailed calculations

NX - number of characters in output histogram for distribution of safety factors

NSTV - number of stochastic variables

BINSIZ - control for number of classes in output histogram. If <1, BINSIZ is used as the class interval of the histogram and number of classes depends on the range of factor of safety values. If >1, BINSIZ is the number of classes required and the interval is determined by range divided by BINSIZ.

F. Stochastic variable cards Format (F3.0,F2.0,3F10.0,9FS.0) NSTV cards required. Each card contains:

STV - index number of stochastic variable

TYPE - code for type of distribution (see below)

ST1

ST2

ST3

ST4(I), I=1,9

} definition of distribution  
see Fig A-6, A-7

The order of the cards is immaterial. TYPE can have the values 1., 2., 3., 4., 5. or 6. For values 1. through 5. the values are as defined in Fig A-6. For TYPE 6., Fig A-7 applies.

G. Distribution cards for piezometric line. Format (F10.0) Skip this card if CODEC = 0.

TYPEW - code for type of distribution (as described for cards F except limited to range 1. through 5.)

H. Distribution definition cards for piezometric line. Format (3F10.0) NW cards - skip if CODEC = 0. Each card contains:

STW1 } distribution parameters as for cards F  
STW2 } (Fig A-6), according to TYPEW  
STW3 }

I. Sensitivity analysis control card Format (3F10.0) Skip if NOSENS = 0. Note that cards I and J must be repeated as a group for each sensitivity variable, ie, NOSENS times, see card B.

NVAR - index number of sensitivity variable - see cards C

NOSTEP - number of different values for sensitivity analysis - maximum 40

PRINT - print control

0. = input and final plot printed

1. = full printout including plot for each value

J. Sensitivity analysis data cards Format (8F10.0) Skip if NOSENS = 0. Note that cards I and J

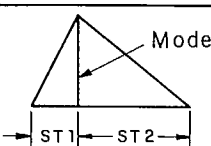
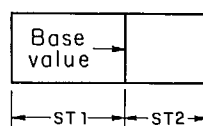
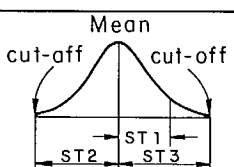
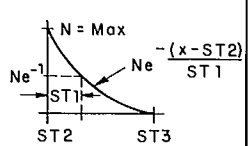
TYPE	ST 1	ST 2	ST 3
1.	Standard deviation	blank	blank
2.	Maximum distance from the mode to the left (lower) side (positive distance)	Maximum distance from the mode to the right (upper) side.	blank 
3.	Maximum distance from the base input value to the left (lower) side (positive distance)	Maximum distance from the base input value to the right (upper) side	blank 
4.	Standard deviation 	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side.
5.	Decay constant 	Lower bound Measured from 0	Upper bound Measured from 0

Fig A-6 - Definition of stochastic input data.

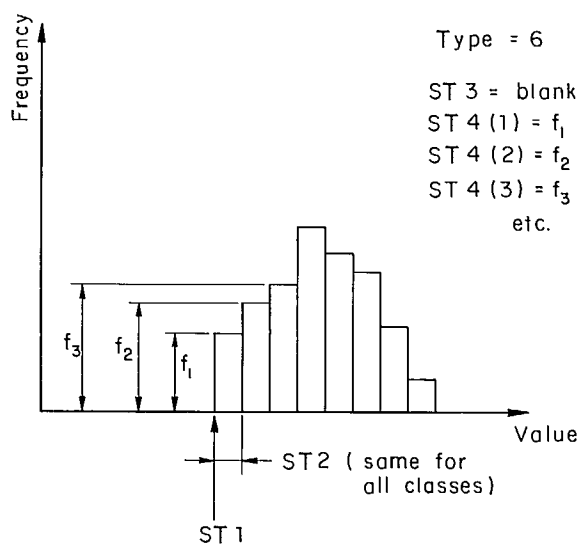


Fig A-7 - Definition of histogram input data.

must be repeated as a group for each sensitivity variable, ie, NOSENS times, see card B.  
Up to 5 cards, containing NOSTEP values of sensitivity variable, 8 values per card.  
Cards K-M give step path simulation data. Do not use sensitivity analysis if step path simulation is used.

K. Step path title card. Format (8A10) Title

L. Step path simulation control card. Format (8F10.0). Two cards

L1 card

MSAMPL - number of sampled paths

MAXSTP - maximum number of steps allowed in a single step path simulation including all major and cross joints sampled

MAXCRS - maximum number of cross joints allowed to cross a single major joint

MSEED - first seed for random number generator

XMAX - maximum x coordinate to which step path may extend; should correspond to tension crack location if CODEA = 1. (card B)

YMAX - maximum y coordinate to which step path may extend. Usually equals H (card C).

BRIDGEM - allowed length for the bridge along major joint to close

BRIDGECL - allowed length for the bridge along cross joint to close

L2 card

IPRT - Step path print code

0. = summary print with plot

1. = as 0. plus additional information

2. = as 1. plus details of each step path

3. = full details of each step including samplings of cross joints

BINSIZ for BETA see card E

BINSIZ for TMLN see card E

BINSIZ for CONTMJ see card E

BINSIZ for TCLEN see card E

BINSIZ for CONTCJ see card E

BINSIZ for VOLUME see card E

M. major and cross joint distribution cards (8 cards) Format (I3,4F8.0,9F5.0)

Each card carries the following data

ITYPE - required distribution - see below

AVERAGE - mean value of relevant variable - see below

ST1	}	definition of distribution, see below
ST2		
ST3		
ST4(I), I=1,9		

The variables defined on the cards - ie, average values and distribution parameters given - are as follows:

M1 card - Length of major joints

M2 card - Dip of major joint

M3 card - Spacing of major joint

M4 card - Overlap of major joint, as a decimal fraction

M5 card - Length of cross joint

M6 card - Dip of cross joint

M7 card - Spacing of cross joint

M8 card - Overlap of cross joint, as a decimal fraction.

ITYPE can have the values 1,2,3,4,5 or 6. For values 1 through 5, Fig A-6 applies. For ITYPE = 6, Fig A-7 applies.

N. Continuation control card. Format (F10.0)

NEXT - 0. = another job follows, go to card A

1. = analysis complete, stop job.

#### Sample Problem

64. In designing the proposed ultimate slope of an open pit mine which is to have a height, (H), of 300 feet (91.4 m), it is desired to have an overall slope of 60° (DIPF = 60.). This angle will be acceptable only if the resulting probability of sliding is 10 per cent or less.

65. The footwall consists of competent rock with two distinct joint sets striking parallel to the proposed ultimate pit slope. These provide potential major and cross joints for step path sliding. Investigation determined that these joint sets are defined by the following statistical parameters:



Parameter	Major Joints	Cross Joints
Dip (normally distributed) mean	40° (DIPM)	80° (DIPC)
standard deviation	2°	2°
Friction angle (normally distributed) mean	30° (PHI)	
standard deviation	1.5°	
Cohesion (normally distributed) mean	2000 lb/ft <sup>2</sup> (C) (47.9 kN/m <sup>2</sup> )	
standard deviation	200 lb/ft <sup>2</sup> (9.6 kN/m <sup>2</sup> )	
Length (exponentially distributed)		
decay constant	6 ft (1.8 m)	3 ft (0.9 m)
lower bound	1 ft (0.3 m)	0.5 ft (0.15 m)
upper bound	∞	∞
Spacing (exponentially distributed)		
decay constant	4 ft (1.2 m)	3 ft (0.9 m)
lower bound	0.5 ft (0.15 m)	0.5 ft (0.15 m)
upper bound	20 ft (6.1 m)	20 ft (6.1 m)
Overlap (uniform distribution)	uniform from 0. to 1.	uniform from 0. to 1.
The strength parameters of the intact rock are determined as:		
Friction angle (normally distributed) mean	45° (PHIROK)	
standard deviation	3°	
Cohesion (normally distributed) mean	25,000 lb/ft <sup>2</sup> (CROK) (1197.5 kN/m <sup>2</sup> )	
standard deviation	8000 lb/ft <sup>2</sup> (383.2 kN/m <sup>2</sup> )	
Tensile strength (normally distributed) mean	5000 lb/ft <sup>2</sup> (TROK) (239.5 kN/m <sup>2</sup> )	
standard deviation	1500 lb/ft <sup>2</sup> (71.9 kN/m <sup>2</sup> )	

66. The in situ unit weight of the rock (DENR) is 160 lb/ft<sup>3</sup> (2.56 t/m<sup>3</sup>) with a standard deviation of 5 lb/ft<sup>3</sup> (0.08 t/m<sup>3</sup>). No external forces will act on the slope (T = 0., THETA = 0., ACCEL = 0.).

67. A hydrological study indicates that the piezometric line for the potential sliding surface with a 60° slope can be approximated as shown in Fig A-8. Determine whether the resulting probability of sliding is acceptable.

#### Procedure

68. Data cards are prepared as described under DATA INPUT. Figure A-9 is a listing of the input cards for this example. After filling out the Header (A) card with an appropriate job description, the Control (B) card is used to specify details of the problem and the type of analysis to be performed. A probabilistic analysis (CALCS = 1.) is required, and a tension crack is not to be included in the analysis (CODEA = 0.). Figure A-8 shows that the piezometric line is to be defined by means of three points (NW = 3.), and because of its uncertainty is to be considered a stochastic variable (CODEC = 1.). Because the step path simulation is to be used, no sensitivity analysis will be employed (NOSENS = 0.), but stability analysis is to be performed (NBETA = 2.).

69. Much of the data required for the Slope Definition (C) cards has already been defined. The distance from the slope crest to the tension crack (L) is left blank since the tension crack definition code on the A card ensures this will not be read. Note that the parameters marked with an asterisk are required only in a step path analyses and when not applicable should be left blank. The beta angle (BETA), the continuities of the major and cross joints (CONTMJ and CONTCJ), and the total lengths of the major and cross joints (TMJL and TCJL) are not known at this stage and so are left blank. These five values will generally be known only if a step path simulation has been performed previously, in which case defining the distributions here and on the Definition of Stochastic Variables (F) cards, and using the stability analysis option with defined step path distributions (NBETA = 2.) will prevent

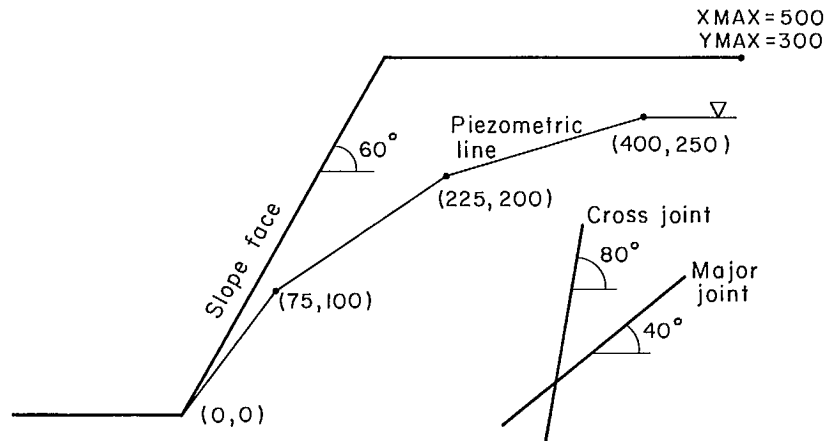


Fig A-8 - Sample problem for step-path sliding.

1234567890RS 061276 SAMPLE STEP PATH SLIDING ANALYSIS

1.	0.	3.	1.	0.	2.				
300.		60.	40.	80.					
		30.	2000.	45.	25000.	5000.	160.		
62.4	0.	0.	0.						
75.	100.	225.	200.	400.	250.				
200.	123.	1.	50.	6.	20.				
11.6.25.	1.		3.	7.	25.	27.	11.	9.	3.
12.1.200.									1.
13.1.3.									
14.4.8000.	25000.	73000.							
15.4.1500.	5000.	14000.							
16.1.5.									
2.									
20.	10.								
30.	20.								
20.	10.								
STEP PATH SIMULATION EXAMPLE									
200.	1000.	10.	123.	500.	300.	20.	20.		
0.	50.	20.	20.	20.	20.	20.	20.		
6	10.	2.	22.	3.	17.	66.	8.	300.	1.
140.	2.								0.
54.	4.	0.5							3.
3.5	.5	.5							
53.	3.	0.5							
180.	2.								
53.	3.	0.5							
30.5	0.5	0.5							
0.									

Fig A-9 - Input data for sample problem.

the regeneration of identical step paths.

70. The Piezometric Line Definition (D) card is used to define the coordinates of points on the piezometric line:  $XW(1) = 75.$ ,  $YW(1) = 100.$ ,  $XW(2) = 225.$ ,  $YW(2) = 200.$ ,  $XW(3) = 400.$ ,  $YW(3) = 250.$

Note that the piezometric line is assumed to pass through the toe of the slope. The coordinates of this point therefore need not be defined.

71. Since a probabilistic slope stability analysis is required, it is necessary to specify

data concerning the Monte Carlo process and the printout required. A sample size of 200 (NSAMPL = 200.) gives reliable results and any odd number can be used to start the random number generator (MFIRST = 123, has arbitrarily been used in this example). A histogram of calculated factors of safety and a table of calculated factors of safety, without details of the calculations, are specified (MPRT = 1.). The histogram is specified as having 20 class intervals (BINSIZ = 20.) and is 50 characters in length (NX = 50.). There are six parameters specified on the Slope Definition card and considered to be stochastic variables (NSTV = 6.). Since option NBETA = 2 is used, the beta angle (BETA), continuities (CONTMJ and CONTCJ), and total joint lengths (TMJL and TCJL) are taken as statistical variables by the program, and their distributions are specified by the program as described above.

72. The distribution of stochastic variables are defined on the Definition Stochastic Variables (F) cards using the index numbers of the stochastic variables specified on the C cards (STV), the distribution definition code to specify the type of distribution (TYPE), and ST1, ST2, ST3 and ST4 to define the limits of the distributions. For example, the friction angle of the major joints is considered to be normally distributed (STV = 11., TYPE = 1.) with a mean of  $30^\circ$  as specified on the C cards (PHI = 30.) and a standard deviation of  $1.5^\circ$  (ST1 = 1.5). Since distributions of the joint orientations are used for generation of the step path but are not sampled during the stability analysis, their distributions need not be defined here. The distribution definition codes are left blank where these parameters are to be determined by the program, ie, for the beta angle and continuities.

73. Since the location of the piezometric line is considered a stochastic variable, the nature of its distribution must be specified on the G card using the distribution definition code. In this case, the distribution is triangular (TYPEW = 2.). All points defined on the piezometric line must have the same type of distribution but may have different ranges, as specified on the Dispersion

Definition for Piezometric Line (H) cards. For example, it is considered that the first point on the piezometric line may vary from 20 ft (6.1 met) below (STW1 = 20.) the level specified on the D card to 10 ft (3.0 met) above it (STW2 = 10.).

74. Since the sensitivity analysis option is not used, the Sensitivity Analysis Control (I) and Sensitivity Analysis Data (J) cards are omitted entirely.

75. The remaining cards concern the simulation of the step path. The Identification (K) card provides a way to identify the step path simulation separately from the stability analysis and can contain any heading which will fit on the card.

76. The Step Path Simulation Control (L) cards control the Monte Carlo simulation of the step path and the plotting of the results in a manner similar to that in which the Probabilistic Analysis Control (E) card controls the probabilistic stability analysis. The total number of step paths to be simulated is specified by MSAMPL (= 200.). Controls on the step path generation are provided by specifying the maximum number of steps which are allowed for any step path (MAXSTP = 1000.) and the maximum number of cross joints allowed to cross a single major joint (MAXCRS = 10.). Setting these to large values will effectively remove any control. The first number of the random number generator can be specified as any odd number; eg, MSEED = 123. is arbitrarily chosen here. Further controls are provided by specifying the maximum distances in the X (XMAX = 500.) and Y (YMAX = 300.) directions to which the step path will be allowed to propagate. XMAX will correspond to the location of the tension crack if there is one, and this will not in general equal L since L is measured from the crest of the slope, YMAX will generally equal the height of the slope. Final controls are provided by specifying the distance over which major joints (BRIDGEM = 20.) and cross joints (BRIDGECL = 20.) are assumed to be able to propagate in the formation of the step path; in other words, the length of rock bridges which will "fail" during step path simulation. Note that values of these parameters which are

large relative to the joint lengths and spacings will virtually assure the formation of a continuous step path and so the shear and tensile strength of the intact rock will not be used in the stability calculation, since no rock bridges will exist. Setting these values to zero will result in the maximum length of rock bridges and, therefore the full effect of intact rock strength will be considered in the stability analysis. Since stability calculations are very sensitive to the presence of intact rock bridges, the conservative assumption is made here that joints will propagate over considerable distances in the simulation of the step path. A print option which gives summary plots and the statistics of important parameters concerning the simulated step paths (IPRT = 0.) will usually suffice for general program operation. The number of characters each class interval of a histogram plot can accommodate (NX = 50.) and the number of class intervals for each parameter plot (BINSIZ(I) = 20., I = 1, 6) are also specified.

77. The distribution of the lengths, dips, spacings, and overlaps for the major and cross joints are specified on the M cards. This input is similar to that of the Definition of Stochastic Variables (F) cards with the exception that each

variable is defined automatically by the sequence of the cards. The average value for each parameter (equivalent to the values specified on the Slope Definition (C) cards) must be specified on the M cards. This applies even where this value has already been specified on the Slope Definition card.

78. Finally, the fact that all input data has been specified is defined on the Continuation Control (N) card (NEXT = 0.).

79. The printed output, as shown in Exhibit A-1, consists initially of a description of all variables which appear in the output of the stability analysis. All names of the variables used in the step path simulation are not included, since these require somewhat more detailed descriptions which are given in the program documentation. The basic input data, some values from intermediate steps in the stability analysis, and the factor of safety are then printed. This enables checking of the input and a hand check of the stability calculation for the basic input data.

80. Next, the probability analysis control specifications are printed, followed by the specified distributions of all input parameters.

## SYSTEM AND OPERATING DOCUMENTATION

### Computer Equipment

81. The program was developed on a CDC 6600 and can therefore be run on any similar machine. It should be noted that because random number generators are machine dependent, it will be necessary to replace subroutine RANDOM if the machine has a word length less than 10 bits.

### Peripheral Equipment

82. Minimum peripheral equipment required is a card reader and a line printer.

### Source Program

83. A tape of PLAFAM is available from the Mining Research Laboratories, CANMET.

### Variables and Subroutines

84. Variables input into the program which can be varied in a sensitivity analysis are as follows:

Input variable

number	Input variable
1	H = slope height
2	L = distance from slope crest to tension crack
3	DIPF = dip of face

4	DIPP = dip of sliding plane (or DIPM = dip of major joints)
5	*DIPC = dip of cross joints
6	*BETA = beta angle
7	*CONTMJ = continuity of major joints
8	*CONTCJ = continuity of cross joints
9	*TMJL = total major joint length
10	*TCJL = total cross joint length
11	PHI = friction angle on sliding plane
12	C = cohesion on sliding plane
13	*PHIROK = friction angle of intact rock
14	*CROK = cohesion of intact rock
15	*TROK = tensile strength of rock
16	DENR = density of rock
17	DENW = density of water
18	T = externally applied load
19	THETA = angle between external load and normal to sliding surface
20	ACCEL = earthquake coefficient as a decimal fraction

\* Input only for a step path analysis

# 85. Subroutines used are:

PLAFAM is the main program which controls sensitivity loop, deterministic or probabilistic branching, and end of job.

INPT reads in program control information and other required input except for step path simulation data.

PLANE performs stability analysis either for plane or for stepped path sliding.

FPRES computes hydrostatic force from piezometric line data.

OUT prints output of deterministic stability analysis.

MONTE executes probability analysis for either plane or stepped path sliding.

MONTOUT prints probability analyses input; contains an entry point SAMPOUT.

SAMPOUT is the entry point in MONTOUT, which prints sampled input and corresponding stability analysis output.

BINPT reads step path simulation input.

RWALK monitors the simulation of sampling joint steps forming a step path.

JNTVEC samples the length, dip, and "overlap factor" of each joint forming a step of the step path.

CROSS samples cross joints for each major joint to determine which cross joints satisfy the criteria for constituting part of the sliding path. Only one major joint is sampled for each cross joint.

ENDWLK determines the coordinates of the end of each step and checks for the end of the step path.

SUMRY provides the statistical summaries of various quantities sampled such as the beta angles, major joint lengths, cross joint lengths, continuity factors, and the area between the beta plane and the step path.

FPLLOT plots the factor of safety against the parameter being varied for a sensitivity analysis.

BETAGEN executes the step path simulation and interfaces with PLAFAM.

STEPSIM controls the calling of the subroutines required for the simulation of the step path.

It also calls the statistical subroutines and transfers the necessary statistical data to PLAFAM.

PLOT plots the probability of sliding for sensitivity analysis.

NORH normalizes input histogram data, ie, to give a cumulative total probability of 1.0.

86. Addition subroutines in the Monte Carlo overlay have been documented separately.

87. Important variables are listed below according to the subroutines in which they are found.

## Subroutine PLANE

A = area of sliding rock mass

BA =  $\beta - \alpha$

BETA = beta angle in degrees, defined as the mean direction of the step path about which the total areas formed by step paths above and below the beta plane are the same

C = cohesive strength of the joints

CE = effective cohesive force

CM = cohesive strength of intact rock

CONTCJ = continuity factor of cross joints

CONTMJ = continuity factor of major joints

DENR = unit weight of the rock

DENW = unit weight of water

DIPC = average dip of the cross ( $\psi$ ) joints in degrees

DIPF = dip of the slope face

DIPM = average dip of the major ( $\alpha$ ) joints in degrees

DIPP = dip of slip plane in degrees

E = earthquake force

EN = average effective normal force on the  $\alpha$  plane

H = slope height

HW = height of the water column in tension crack measured from the sliding plane or  $\beta$  plane if the step path option is used

ICLK = code to check whether hydrostatic forces have to be computed

KINCK = code to check whether  $DIPF \leq DIPP$

L = length from the crest to the tension crack along the top surface

NBETA = step path simulation code

NW = number of points defining piezometric line segments

PHI = average friction angle of joints in degrees

PHIM = average friction angle of the intact rock in degrees

SHEAR = average shearing strength mobilized along the sliding path

T = external force

TCLN = average total length of cross joints including intact portion

TENST = average tensile strength mobilized from cross joints

THETA = dip of the external force

TM = average tensile strength of the intact rock

TMLN = average total length of major joints including intact portion

U = uplift force on the average sliding plane

V = horizontal force due to the presence of water in the tension crack

W = weight of the rock mass

XW = X coordinates of the points defining piezometric line

X1 = X coordinate of the crest of the slope

X2 = X coordinate of the exit point of the shear surface at the top of the slope

X3 = X coordinate of the bottom of the tension crack if it exists (= X2 always)

YW = Y coordinates of the points defining the piezometric line

Y1 = Y coordinate of the crest of the slope

Y2 = Y coordinate of the exit point of the shear surface at the top of the slope

Y3 = Y coordinate of the bottom of the tension crack if it exists

Z = height of the tension crack

#### Data Structures

88. Not applicable

#### Storage Requirement

89. Approximately 45,000 octal words.

#### Maintenance and Updates

90. Program development completed November, 1975, and modified slightly by R. Sage (CANMET) December, 1976, ie, histogram probability input added.

#### Operating Instructions

91. There are no special instructions for this program.

#### Operating Messages

92. No special messages are produced by the program.

#### Control Cards

93. Standard compile and execute cards are all that are required to run the program.

#### Error Recovery

94. Not applicable.

#### Run Time

95. Each factor of safety calculation requires approximately 2.4 seconds of CDC 6600 CPU time using the step path option, and 0.02 CP seconds without this option. The sample problem took 40 seconds of CPU time to run.





EXHIBIT A-1

LISTING OF OUTPUT FOR SAMPLE PROGRAM



## DESCRIPTION OF VARIABLES IN LIMIT EQUILIRRIUM ANALYSIS OF PLANE AND STEP PATH SLIDING

ACCEL = PSEUDO-EARTHQUAKE FORCE COEFF. AS A FRACTION OF GRAVITATIONAL ACCELERATION  
 RETA = ANGLE BETWEEN AVERAGE SLIDING PLANE AND HORIZONTAL  
 C = COHESION OF JOINT  
 CALCS = 0 IF DETERMINISTIC ANALYSIS  
 1 IF PROBABILISTIC ANALYSIS  
 CODFA = 0 IF NO TENSION CRACK  
 = 1 IF TENSION CRACK  
 CODEC = 0 IF PIEZOMETRIC LINE IS NOT SAMPLED  
 1 IF PIEZOMETRIC LINE IS SAMPLED  
 CONTCJ = CONTINUITY FACTOR IN CROSS JOINT STEPS  
 CONTMJ = CONTINUITY FACTOR IN MAJOR JOINT STEPS  
 CROK = COHESION OF INTACT ROCK  
 WENR = UNIT WEIGHT OF ROCK  
 WENW = UNIT WEIGHT OF WATER  
 DIPC = DIP OF CROSS JOINT(AVERAGE VALUE IF PROBABILISTIC ANALYSIS)  
 DIPF = DIP OF SLOPE FACE  
 DIPR(M) = DIP OF SLIDING PLANE (OF MAJOR JOINT IF STEP PATH SLIDING) (AVERAGE VALUE IF PROBABILISTIC RUN)  
 H = SLOPE HEIGHT  
 HW = HEIGHT OF WATER IN TENSION CRACK  
 FS = FACTOR OF SAFETY  
 L = DISTANCE FROM CREST OF SLOPE TO TENSION CRACK  
 POSITIVE IF BEHIND THE CREST, OTHERWISE NEG.  
 NRETA = 0 IF PLANE SLIDING ANALYSIS  
 1 IF STEP PATH SLIDING ANALYSIS WITH STEP PATH DEFINED DIRECTLY BY USER INPUT  
 2 IF STEP PATH SLIDING ANALYSIS WITH STEP PATH SIMULATION BY PROGRAM  
 3 IF STEP PATH SIMULATION BY PROGRAM ONLY (NO STABILITY ANALYSIS)  
 NOSENS = NO. OF SENSITIVITY VARIABLES  
 NW = 0 IF NO PIEZOMETRIC LINE IS CONSIDERED, OTHERWISE  
 NO. OF POINTS DEFINING PIEZOMETRIC LINE EXCLUDING THE FIRST POINT (ASSUMED TO BE TOE OF SLOPE)  
 PHI = FRICTION ANGLE OF JOINT  
 PHIROK = FRICTION ANGLE OF INTACT ROCK  
 T = EXTERNALLY APPLIED FORCE  
 TCJL = TOTAL LENGTHS OF STEPS IN CROSS JOINT DIRECTIONS  
 TCLEN = THE SAME AS THE ABOVE  
 THETA = DIP OF EXTERNAL FORCE  
 TMJL = TOTAL LENGTHS OF STEPS IN MAJOR JOINT DIRECTIONS  
 TMLEN = THE SAME AS THE ABOVE  
 TROK = TENSILE STRENGTH OF ROCK  
 U = UPLIFT FORCE DUE TO WATER  
 V = HYDROSTATIC FORCE DUE TO WATER IN TENSION CRACK  
 W = GRAVITATIONAL FORCE ON SLIDING MASS  
 X2 = X-COORD. OF TOP OF TENSION CRACK; IF NO TENSION CRACK, THE END OF SLIDING PATH  
 X3 = X-COORD. OF BOTTOM OF TENSION CRACK; IF NO TENSION CRACK, THE END OF SLIDING PATH  
 XW = X-COORD. OF POINTS DEFINING PIEZOMETRIC LINE  
 YW = Y-COORD. OF POINTS DEFINING PIEZOMETRIC LINE  
 Z = DEPTH OF TENSION CRACK

\*\*\*\*\*  
 BETA GENERATION INPUT  
 \*\*\*\*\*

## STEP PATH SIMULATION EXAMPLE

SAMPLE SIZE	MAX STEPS	MAX CROSS	WSEED	MAXIMUM X-COORD	MAXIMUM Y-COORD	ALLOWED MR-LENG	ALLOWED CR-LENG
200	1000	10	123	500.000	300.000	20.000	20.000
IPRT	NX	BETA RINSIZE	TMJL RINSIZE	CONTMJ RINSIZE	TCJL RINSIZE	CONTCJ RINSIZE	VOLUME RINSIZE
0	50	20.000	20.000	20.000	20.000	20.000	20.000

## MAJOR JOINT DATA

DIST. TYPE	AVERAGE	ST1	ST2	ST3	HISTOGRAM									
LENGTH HISTOGRAM	-0.000	10.000	2.000	-0.000	22.	3.	17.	66.	8.	300.	1.	0.	3.	
DIP NORMAL	40.000	2.000	-0.000	-0.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	
SPACING EXPNENTIAL	4.000	4.000	.500	20.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	
OVERLAP UNIFORM	.500	.500	.500	-0.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	

## CROSS JOINT DATA

DIST. TYPE	AVERAGE	ST1	ST2	ST3	HISTOGRAM									
LENGTH EXPNENTIAL	3.000	3.000	.500	-0.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	
DIP NORMAL	40.000	2.000	-0.000	-0.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	
SPACING EXPNENTIAL	3.000	3.000	.500	20.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	
OVERLAP UNIFORM	.500	.500	.500	-0.000	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	

REQUIRED VARIABLE SIZE MEMORIES = 1211 PLUS 2\*(NCLASS+1)

```
*****
BETA GENERATION OUTPUT ...DETAIL 0...
*****
```

\*\*\*\*\*  
SAMPLED BETAS  
\*\*\*\*\*

445952F+02	444114E+02	444732F+02	445093F+02	442696F+02	445951F+02	442498E+02	444962E+02	446937F+02	444083E+02
445062F+02	444118E+02	444965E+02	447008F+02	446890F+02	445598E+02	442555E+02	446054E+02	445913E+02	444319F+02
444680F+02	445934F+02	447945E+02	445375F+02	444636F+02	445142E+02	445317E+02	446098E+02	446797F+02	445871E+02
443414F+02	443998E+02	444898E+02	444299E+02	444970F+02	445624E+02	446768E+02	447322E+02	446886E+02	446841F+02
445118F+02	445934F+02	444898E+02	444299E+02	444970F+02	445624E+02	446768E+02	447322E+02	446886E+02	446841F+02
445320F+02	445277F+02	444922F+02	444085E+02	444817E+02	445927E+02	447310E+02	447017E+02	447171E+02	446364F+02
445544F+02	445991E+02	445327F+02	445782F+02	445128E+02	447446E+02	445443E+02	445433F+02	446999E+02	447360F+02
445231F+02	445264E+02	446838F+02	445507E+02	442216E+02	446934F+02	446230E+02	447688F+02	446653E+02	446110E+02
445924E+02	446266E+02	443802E+02	445463E+02	445052E+02	445575E+02	445575E+02	444218E+02	446261E+02	443440E+02
445924E+02	446266E+02	443802E+02	445463E+02	445052E+02	445575E+02	445575E+02	444218E+02	446261E+02	443440E+02
444898F+02	446053F+02	447368F+02	445121F+02	447310F+02	445678F+02	445107E+02	446189E+02	445251F+02	446004F+02
445615F+02	445150F+02	445484E+02	444283F+02	446401E+02	445306E+02	446135E+02	445343E+02	446884E+02	444240F+02
445545F+02	447712E+02	445117E+02	447916E+02	443592E+02	446544E+02	442333F+02	447626E+02	448377E+02	445621E+02
445150E+02	445415F+02	449290E+02	445366E+02	444394E+02	443932E+02	447186E+02	448055F+02	448958F+02	445085F+02
445150E+02	445415F+02	449290E+02	445366E+02	444394E+02	443932E+02	447186E+02	448055F+02	448958F+02	445085F+02
447165F+02	446670E+02	446102E+02	446518F+02	445437E+02	447046E+02	446711E+02	443405E+02	446420E+02	445929F+02
443319F+02	443554E+02	446525F+02	447969E+02	445008E+02	445321F+02	445111E+02	443629F+02	445125F+02	443122E+02
445999F+02	443960E+02	444444E+02	447010E+02	446067E+02	443455E+02	447375E+02	443286E+02	446050E+02	446142E+02
443088F+02	445701E+02	447575E+02	447595E+02	444477E+02	445955E+02	445134E+02	444093E+02	444737E+02	445815F+02

MINIMUM = 42.49842 MAXIMUM = 49.68344

### FREQUENCY DISTRIBUTION

		FREQUENCY							
		0	10	20	30	40	50		
CLASS	INTERVAL	I.....I.....I.....I.....I.....I						FRQ	PCT
1	42.50	42.86	.X					1	.5
2	42.86	43.22	.XX					2	1.0
3	43.22	43.58	.XXXXXXXX					7	3.5
4	43.58	43.94	.XXXXXX					5	2.5
5	43.94	44.29	.XXXXXXXXXXXX					12	6.0
6	44.29	44.65	.XXXXXXXXXXXX					11	5.5
7	44.65	45.01	.XXXXXXXXXXXX					13	6.5
8	45.01	45.37	.XXXXXXXXXXXXXXXXXXXX					19	9.5
9	45.37	45.73	.XXXXXXXXXXXXXXXXXXXX					16	8.0
10	45.73	46.09	.XXXXXXXXXXXXXXXXXXXX					20	10.0
11	46.09	46.45	.XXXXXXXXXXXXXXXXXXXX					23	11.5
12	46.45	46.81	.XXXXXXXXXXXXXXX					16	8.0
13	46.81	47.17	.XXXXXXXXXXXXXXX					14	7.0
14	47.17	47.53	.XXXXXXXXXXXXXXX					17	8.5
15	47.53	47.89	.XXXXXX					5	2.5
16	47.89	48.25	.XXXXXX					5	2.5
17	48.25	48.61	.XXX					3	1.5
18	48.61	48.96	.XXXX					4	2.0
19	48.96	49.32	.X					1	.5
20	49.32	49.68	.XXXXXX					6	3.0
		I.....I.....I.....I.....I.....I							
		0	10	20	30	40	50		

## SAMPLE STATISTICS

MEAN= 45.979 S.D.= 1.461 SKEWNESS= .047 KURTOSIS= 2.87 SAMPLE SIZE= 200

\*\*\*\*\*  
SAMPLED MAJOR JOINT LENGTHS  
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.34766F+03 .34195F+03 .34540F+03 .37599F+03 .36292F+03 .37410F+03 .40224E+03 .37918F+03 .34664F+03 .36672E+03
.34531F+03 .34956E+03 .37311F+03 .35409F+03 .35940E+03 .35532F+03 .36475E+03 .36443F+03 .35734F+03 .37547F+03
.34261F+03 .36577F+03 .37102F+03 .34981F+03 .34082F+03 .34413F+03 .35249E+03 .35219E+03 .32671E+03 .33535F+03
.32653F+03 .32870F+03 .35265F+03 .36911F+03 .36545F+03 .34247F+03 .37313E+03 .34140F+03 .34704F+03 .35378F+03
.34332F+03 .35896F+03 .34600F+03 .35950F+03 .34390F+03 .34330F+03 .31006E+03 .33186E+03 .37114F+03 .29406F+03
.35442F+03 .36223F+03 .32674E+03 .35746F+03 .35196E+03 .36620E+03 .33556E+03 .33726F+03 .33655E+03 .37476F+03
.35362F+03 .36640E+03 .37135F+03 .35245F+03 .35421F+03 .32965E+03 .36650E+03 .37898F+03 .36941E+03 .32733F+03
.35945F+03 .37151E+03 .35892E+03 .36127F+03 .34572F+03 .32317E+03 .36693E+03 .38688E+03 .35698F+03 .32301F+03
.35746F+03 .36936E+03 .37936E+03 .35981F+03 .35970E+03 .34072E+03 .34217E+03 .37392E+03 .37504F+03 .34800E+03
.31370F+03 .36032E+03 .36637E+03 .37426F+03 .34424E+03 .37410F+03 .33494E+03 .34732E+03 .33908F+03 .35128F+03
.35955F+03 .36392E+03 .33766F+03 .34112F+03 .32794F+03 .37806F+03 .37545E+03 .37200E+03 .36721F+03 .34898F+03
.36488F+03 .36554F+03 .34205F+03 .34705F+03 .34924F+03 .36049E+03 .35647E+03 .36618F+03 .33511F+03 .36793F+03
.34037F+03 .33021F+03 .35579F+03 .33464F+03 .35702F+03 .32993F+03 .34358F+03 .32674E+03 .33021F+03 .36369F+03
.30950F+03 .36332E+03 .32486E+03 .35365F+03 .36605F+03 .34097F+03 .34699F+03 .33036F+03 .34707F+03 .35647F+03
.34610F+03 .35373F+03 .34276E+03 .32973F+03 .35743F+03 .36599F+03 .37382E+03 .36371E+03 .34231F+03 .34561F+03
.34557E+03 .34409E+03 .37006E+03 .35360F+03 .36390F+03 .34582F+03 .34868E+03 .40120E+03 .35400F+03 .36387F+03
.34196F+03 .40045E+03 .37883E+03 .33504F+03 .35584E+03 .35505F+03 .36182F+03 .37489E+03 .36414F+03 .34891F+03
.34540F+03 .35846E+03 .34172F+03 .35029F+03 .35884F+03 .37643E+03 .33838E+03 .39204E+03 .34498F+03 .35007F+03
.32104F+03 .35794E+03 .32995E+03 .34457F+03 .34472E+03 .40853E+03 .35627E+03 .37513E+03 .35463E+03 .35553F+03
.34788F+03 .34295E+03 .34656E+03 .34271F+03 .34679E+03 .35895E+03 .37923E+03 .40254E+03 .37268F+03 .36760E+03
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MINIMUM = 294.05659 MAXIMUM = 408.53431

# ----- FREQUENCY DISTRIBUTION -----

		FREQUENCY							
		0	10	20	30	40	50		
CLASS	INTERVAL	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	FRQ	PCT
1	294.06 299.78	.X						1	.5
2	299.78 305.50	.						0	0.0
3	305.50 311.23	.XX						2	1.0
4	311.23 316.95	.X						1	.5
5	316.95 322.68	.X						1	.5
6	322.68 328.40	.XXXXXXXXXX						8	4.0
7	328.40 334.12	.XXXXXXXXXXXX						10	5.0
8	334.12 339.85	.XXXXXXXXXXXX						11	5.5
9	339.85 345.57	.XXXXXXXXXXXX						12	6.0
10	345.57 351.30	.XXXXXXXXXXXXXXXXXXXX						21	10.5
11	351.30 357.02	.XXXXXXXXXXXXXXXXXXXX						22	11.0
12	357.02 362.74	.XXXXXXXXXXXXXXXXXXXX						27	13.5
13	362.74 368.47	.XXXXXXXXXXXXXXXXXXXX						30	15.0
14	368.47 374.19	.XXXXXXXXXXXXXXXXXXXX						17	8.5
15	374.19 379.92	.XXXXXXXXXXXXXX						15	7.5
16	379.92 385.64	.XXXXXXXXXXXX						11	5.5
17	385.64 391.36	.XXXXX						4	2.0
18	391.36 397.09	.X						1	.5
19	397.09 402.81	.XXXXX						5	2.5
20	402.81 408.54	.X						1	.5
		I.....I	I.....I	I.....I	I.....I	I.....I	I.....I		
		0	10	20	30	40	50		

# ----- SAMPLE STATISTICS -----

MEAN= 357.914 S.D.= 19.020 SKEWNESS= -.035 KURTOSIS= 3.34 SAMPLE SIZE= 200

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FREQUENCY DISTRIBUTION AND SAMPLE STATISTICS SKIPPED
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 SAMPLED CROSS JOINT LENGTHS  
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7.79375E+02	6.67094E+02	6.71709E+02	5.94997E+02	6.63486E+02	5.97803E+02	6.45360E+02	5.82102E+02	7.79575E+02	6.33686E+02
5.54510E+02	6.67004E+02	6.53800E+02	7.74767E+02	6.94114E+02	7.51060E+02	6.66482E+02	6.44774E+02	7.72132E+02	6.17309E+02
5.54797E+02	6.63575E+02	6.85437E+02	7.76346E+02	7.74446E+02	6.18628E+02	7.61517E+02	7.63308E+02	9.33771E+02	6.48897E+02
7.79375E+02	6.67094E+02	6.71709E+02	5.94997E+02	6.63486E+02	5.97803E+02	6.45360E+02	5.82102E+02	7.79575E+02	6.33686E+02
8.05197E+02	7.74040E+02	7.70336E+02	7.73803E+02	8.29040E+02	7.78439E+02	1.01617E+03	7.92408E+02	6.67471E+02	1.12182E+03
7.77048E+02	7.73777E+02	6.16095E+02	6.82477E+02	7.76080E+02	6.64640E+02	6.86597E+02	6.83624E+02	7.90824E+02	6.45611E+02
7.54282E+02	7.70792E+02	6.12919E+02	7.65897E+02	7.74022E+02	6.91212E+02	6.91946E+02	5.91049E+02	6.89733E+02	7.62377E+02
7.77048E+02	7.73777E+02	6.16095E+02	6.82477E+02	7.76080E+02	6.64640E+02	6.86597E+02	6.83624E+02	7.90824E+02	6.45611E+02
7.74762E+02	6.79282E+02	6.53645E+02	7.71796E+02	7.75250E+02	6.59120E+02	6.73555E+02	6.62638E+02	6.64487E+02	7.82445E+02
1.01413E+03	7.74005E+02	6.64601E+02	6.64952E+02	6.80261E+02	6.67677E+02	8.07164E+02	8.11615E+02	8.3185E+02	8.08534E+02
7.77048E+02	7.73777E+02	6.16095E+02	6.82477E+02	7.76080E+02	6.64640E+02	6.86597E+02	6.83624E+02	7.90824E+02	6.45611E+02
6.67252E+02	6.65219E+02	7.13082E+02	5.51181E+02	7.60172E+02	6.65151E+02	7.73419E+02	6.65470E+02	6.66313E+02	6.79313E+02
7.74338E+02	8.43646E+02	7.75444E+02	8.59571E+02	7.74179E+02	8.95456E+02	5.73746E+02	9.36177E+02	8.98373E+02	6.98262E+02
1.02363E+03	6.64877E+02	6.18363E+02	7.78533E+02	7.70308E+02	7.12373E+02	8.11306E+02	8.98734E+02	7.74474E+02	7.73777E+02
6.67252E+02	6.65219E+02	7.13082E+02	5.51181E+02	7.60172E+02	6.65151E+02	7.73419E+02	6.65470E+02	6.66313E+02	6.79313E+02
6.90107E+02	8.25797E+02	6.88233E+02	7.74435E+02	6.80545E+02	7.72666E+02	7.74733E+02	1.01712E+03	7.73487E+02	6.83245E+02
5.57161E+02	6.44955E+02	5.75911E+02	9.51767E+02	7.70217E+02	7.78264E+02	7.72697E+02	6.62577E+02	6.87233E+02	6.11181E+02
5.57161E+02	6.44955E+02	5.75911E+02	9.51767E+02	7.70217E+02	7.78264E+02	7.72697E+02	6.62577E+02	6.87233E+02	6.11181E+02
9.05057E+02	7.71753E+02	6.44272E+02	7.92872E+02	6.75733E+02	7.97471E+02	7.72450E+02	6.60934E+02	7.71161E+02	7.73910E+02
7.77937E+02	6.53090E+02	6.80779E+02	6.81019E+02	6.52273E+02	6.64949E+02	6.41898E+02	6.48912E+02	6.64636E+02	6.66192E+02

### FREQUENCY DISTRIBUTION

			FREQUENCY							
			0	10	20	30	40	50		
CLASS	INTERVAL	I	I	I	I	I	I	I	FREQ	PCT
1	39.74 43.36	.xxx						.	3	1.5
2	43.36 46.99	.xxx						.	3	1.5
3	46.99 50.61	.x						.	1	.5
4	50.61 54.23	.xxxx						.	4	2.0
5	54.23 57.85	.xxxxxxxx						.	9	4.5
6	57.85 61.47	.xxxxxxxxxxxxxxxx						.	17	8.5
7	61.47 65.10	.xxxxxxxxxxxxxxxx						.	15	7.5
8	65.10 68.72	.xxxxxxxxxxxxxxxxxxxxxxxx						.	24	12.0
9	68.72 72.34	.xxxxxxxxxxxxxxxxxxxx						.	20	10.0
10	72.34 75.96	.xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx						.	31	15.5
11	75.96 79.58	.xxxxxxxxxxxxxxxxxxxxxxxx						.	21	10.5
12	79.58 83.21	.xxxxxxxxxxxxxxxx						.	15	7.5
13	83.21 86.83	.xxxxxxxxxxxx						.	12	6.0
14	86.83 90.45	.xxxxxxx						.	7	3.5
15	90.45 94.07	.xxxxxxxxxxx						.	11	5.5
16	94.07 97.69	.xxx						.	3	1.5
17	97.69 101.32	.						.	0	0.0
18	101.32 104.94	.xxx						.	3	1.5
19	104.94 108.56	.						.	0	0.0
20	108.56 112.18	.x						.	1	.5
			I	I	I	I	I	I		
			0	10	20	30	40	50		

## SAMPLE STATISTICS

MEAN= 72.619 S.D.= 12.429 SKEWNESS= .006 KURTOSIS= 3.28 SAMPLE SIZE= 200

MINIMUM = 1.00000 MAXIMUM = 1.00000

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*****
FREQUENCY DISTRIBUTION AND SAMPLE STATISTICS SKIPPED
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SAMPLED VOLUME

MINIMUM = -3215.95485    MAXIMUM = 3814.71767

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FREQUENCY DISTRIBUTION

[illegible]

\* INTERVAL VALUES IN UNIT OF 1000.

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SAMPLE STATISTICS

MEAN= 327,487      S.D.= 1190,156      SKEWNESS= -,000      KURTOSIS= 3,26      SAMPLE SIZE= 200

SEE DESCRIPTION OF VARIABLES ON FIRST PAGE OF OUTPUT

CALCS 1.	CODEA 0.	NW 3	CODEC 1.	NOSFMS 0	NBETA 2					
H	L	DIPF	DIPP(M)	DIPC	BETA	CONTMJ	CONTCJ	TMJL	TCJL	
300.00	-0.00	60.00	40.00	80.00	45.98	1.00	1.00	357.91	72.62	
PHI	C	PHIROK	CROK	TROK	DENR	DENW	T	THETA	ACCEL	
30.00	2000.00	45.00	25000.00	5000.00	160.00	62.40	0.00	0.00	0.00	

POINTS ON PIEZOMETRIC LINE

PT. NO.	1	2	3	4
XW	0.00	75.00	225.00	400.00
YW	0.00	100.00	200.00	250.00

U	V	W	Z	HW	X2	X3	TMLEN	TCLEN	F5
136562.	0.	2801180.	0.00	0.00	289.92	289.92	357.91	72.62	1.03

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 PROBABILITY ANALYSIS - DETAIL OF INPUT  
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NO. OF SAMPLES	1ST RAND NO. SEED	PRINT CODE	GRAPH SIZE	STAT VARS	NO. OF CLASSES
200.00	123.00	1.00	50.00	6.00	20.00

RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = TRUNCATED GAUSSIAN, TYPES = EXPONENTIAL,  
 TYPE 6 = HISTOGRAM INPUT, TYPE 0 = NO SAMPLING DONE

VARIABLE	H	L	DIPF	DIPP(M)	DIPC	BETA	CONTMJ	CONTCJ	TMJL	TCJL
BASE	300.00	-0.00	60.00	40.00	80.00	45.98	1.00	1.00	357.91	72.62
TYPE	0	0	0	0	0	1	0	0	4	1
ST1	0.00	0.00	0.00	0.00	0.00	1.46	0.00	0.00	19.02	12.43
ST2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	63.86	0.00
ST3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VARIABLE	PHI	C	PHIROK	CROK	TROK	DENR	DENW	T	THETA	ACCEL
BASE	30.00	2000.00	45.00	25000.00	5000.00	160.00	62.40	0.00	0.00	0.00
TYPE	6	1	1	4	4	1	0	0	0	0
ST1	25.00	200.00	3.00	8000.00	1500.00	5.00	0.00	0.00	0.00	0.00
ST2	1.00	0.00	0.00	25000.00	5000.00	0.00	0.00	0.00	0.00	0.00
ST3	-0.00	0.00	0.00	73000.00	14000.00	0.00	0.00	0.00	0.00	0.00
H	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I V	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S A	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T L	27.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O U	11.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G E	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R S	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

DISTRIBUTION FOR VERTICAL WATER LINE SAMPLING - TYPE = 2

PT. NO.	1	2	3	4
XW	0.00	75.00	225.00	400.00
YW	0.00	100.00	200.00	250.00
STW1	0.00	20.00	30.00	20.00
STW2	0.00	10.00	20.00	10.00



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 SAMPLE VALUES FOR FACTOR OF SAFETY  
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.97434	1.10485	1.04369	1.05889	1.01002	1.09594	.93088	.95464	.97736	.93446
.96673	1.11154	1.06401	1.05496	1.01780	1.03087	.90887	.94788	1.22670	.94547
.92661	1.06884	.99039	.98644	.94484	1.07311	.88779	.83926	1.04669	1.04548
.98412	.87753	.95082	1.16213	.91800	.89767	.97870	.88742	.94318	1.16808
1.00087	.95201	.98565	.98537	.82949	.90936	.83316	.96803	.88698	.99410
.93519	.92873	.94545	.86773	.88526	.90143	1.00316	.99462	1.08745	.95948
.97694	.88299	.87341	1.21359	.89869	1.02264	.99982	.97137	1.15237	.95564
1.04560	.91799	.90426	.98305	.97523	.95993	.91061	1.00706	1.12829	1.22266
1.02010	.94450	1.02524	1.10955	.94844	.95270	.94695	1.05512	.99743	.96824
1.10519	.92296	1.12578	.95671	.81526	.97198	.99999	.93087	.97412	1.13711
.93287	.95221	.99862	1.01658	.86602	.99317	1.00402	.95310	1.03847	.98428
.98518	1.01581	1.07474	.98944	1.05608	1.21524	.99061	.94629	1.08698	.95848
.93265	1.03420	.89923	.99909	1.08940	1.10450	.89356	1.06079	1.04780	.83324
.85372	1.05723	.98277	1.04433	1.05162	.89911	.99470	1.03162	.82794	.88920
.92819	1.04362	.98412	.99670	.98317	.97648	.95860	.89949	.98848	.97226
1.00371	1.00203	1.01302	.90401	.92378	.94726	.94070	.90606	1.04974	1.08612
.89102	1.08244	1.03467	.96044	.84208	.88462	.86170	1.02566	.96633	.91735
.99312	.96695	.92535	1.08922	.99105	1.01718	1.02184	.94944	1.10066	1.15948
1.14954	.87571	.95477	.89635	1.04336	.89216	.95357	.86872	1.00577	1.00310
.88825	.86587	.92049	1.05356	.98082	.99481	1.00865	.96031	.97471	1.04591

MIN F.S.= .81536 MAX F.S.= 1.22670

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 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS	INTERVAL	FREQUENCY						FRO	PCT	
		0	10	20	30	40	50			
1	.82	.84	XXXXXXX						7	3.5
2	.84	.86	XXX						3	1.5
3	.86	.88	XXXXXXXXXX						8	4.0
4	.88	.90	XXXXXXXXXXXXXX						13	6.5
5	.90	.92	XXXXXXXXXXXXXXXXXX						15	7.5
6	.92	.94	XXXXXXXXXXXXXX						11	5.5
7	.94	.96	XXXXXXXXXXXXXXXXXXXXXX						22	11.0
8	.96	.98	XXXXXXXXXXXXXXXXXXXXXX						20	10.0
9	.98	1.00	XXXXXXXXXXXXXXXXXXXXXX						29	14.5
10	1.00	1.02	XXXXXXXXXXXXXXXXXXXXXX						16	8.0
11	1.02	1.04	XXXXXXXXXXXX						9	4.5
12	1.04	1.06	XXXXXXXXXXXXXXXXXXXXXX						18	9.0
13	1.06	1.08	XXXXXX						5	2.5
14	1.08	1.10	XXXXXXX						7	3.5
15	1.10	1.12	XXXXXX						5	2.5
16	1.12	1.14	XXX						3	1.5
17	1.14	1.17	XXXXX						4	2.0
18	1.17	1.19	X						1	.5
19	1.19	1.21	.						0	0.0
20	1.21	1.23	XXXX						4	2.0

-----  
 SAMPLE STATISTICS  
 -----

MEAN= .983 S.D.= .083 SKEWNESS= .223 KURTOSIS= 3.26 SAMPLE SIZE= 200

-----  
 PROBABILITY OF SLIDING  
 -----

P.F.= 58.25 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = .983 AND STD. DEV. = .083  
 P.F.= 64.00 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 0

## REFERENCES

A-1. Call, R.D. Unpublished report, CANMET, Dept. of Energy, Mines and Resources, Ottawa; 1974.

A-2. Jennings, J.E. "A mathematical theory for the calculation of the stability of slopes in open cast mines"; Symposium on planning open pit mines, South African Institute of Mining and Metallurgy, Johannesburg; 1970.

A-3. Jaeger, J.C. "Friction of rock slopes and stability of rock slopes"; Geotechnique 21, no. 2, pp 97-134; 1971.

## APPENDIX B

### PROGRAM DOCUMENTATION OF TWOBAM

(two-block failure analysis including Monte Carlo simulation)



## ABSTRACT

TWOBAM performs a limit equilibrium analysis on a two-dimensional two-block system composed of a passive block and an active or driving block. Cohesive forces on the shear planes, water and external forces can be accounted for in the analysis. The stability of the system is expressed in terms of ratio of the weights of the active and passive blocks, as well as of the more conventional factor of safety. All input parameters can be varied automatically to determine the sensitivity of the stability to those parameters, and the results of this study can be plotted automatically. A Monte Carlo overlay option provides a means for determining slope reliability.

## PROGRAM IDENTIFICATION

Program title: Two-Block Sliding Analysis

Program code name: TWOBAM (TWO-BLOCK SLIDING ANALYSIS INCLUDING MONTE CARLO SIMULATION)

Writer: H.S. Kim and A. Bealer

Organization: Dames & Moore for Canada Centre for Mineral and Energy Technology

Date: September, 1975

Updates: None

Source language: FORTRAN IV

Availability: Canada Centre for Mineral and Energy Technology, 555 Booth St., Ottawa K1A 0G1 Canada.

Disclaimer: Neither the authors nor the Mining Research Laboratories can accept any responsibility for the accuracy of results produced by this program.

## THEORY

### Introduction

1. TWOBAM performs a limit equilibrium analysis of the stability of a system of two blocks considered in two dimensions. It is intended primarily for use in analyzing the stability of rock slopes in which the blocks are defined by geological discontinuities, as investigated by Kuykendall and Goodman (B-1). It is also applicable to other geotechnical problems, such as the stability of sloping core earth dams (B-2).

2. Typical geometries which fall within the two-block classification are shown in Fig B-1. The program can account for different shear strengths on each of the three sliding surfaces and for a wide range of geometrical configurations. Water is defined by means of a linear segmented piezometric line. Moment equilibrium is not considered.

3. The ratio of the weights of the passive and active blocks at the limiting equilibrium condition (WP/WA limiting) provides a convenient measure of the stability of the two-block system. Given the geometry and material properties of a system, the weight ratio of the two blocks (WP/WA) is determined, and a stability factor is calculated as

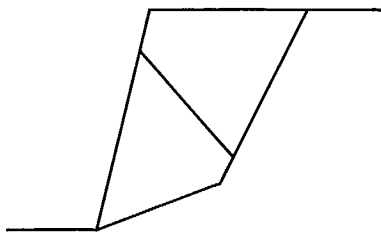
$$\text{S.F.} = (\text{WP/WA}) - (\text{WP/WA limiting})$$

4. A stability factor greater than zero indicates the system is stable; a value less than zero indicates instability. The more conventional factor of safety, defined as the ratio of resisting forces to the driving forces for the passive block with the active block at the limiting equilibrium condition, is also calculated.

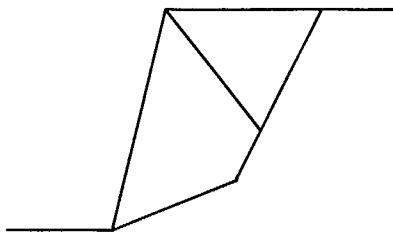
5. The effect of input uncertainties can be assessed quantitatively by means of the Monte Carlo simulation option. Random samplings of input parameters from their defined distributions are used for the repeated calculation of the stability factor and factor of safety. The probability of the factor of safety being less than the limiting equilibrium condition is taken as the probability of instability.

6. Figure B-2 is a diagram of a typical two-block geometry showing the input parameters which define the system. Note that the top surface is assumed to be horizontal and that only one exit point of the shear planes need be defined if these three planes intersect at a point. Kuykendall and Goodman have established the following criteria for the definition of a two-block problem for the friction-only case (B-1):

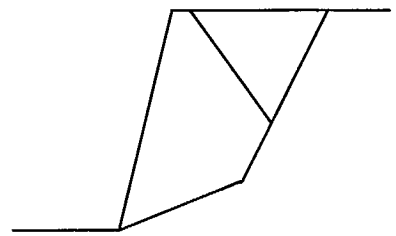
$$\alpha_1 \text{ must be greater than } \phi_1 \\ (\phi_1 = \text{friction angle on plane 1});$$



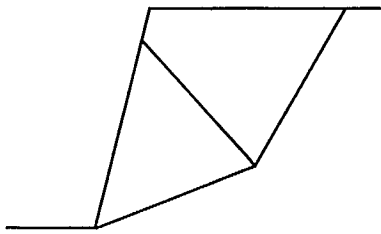
(a)



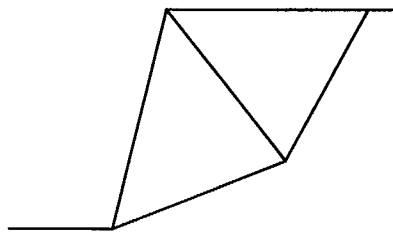
(b)



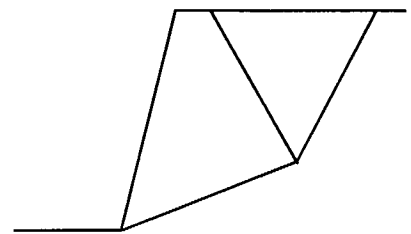
(c)



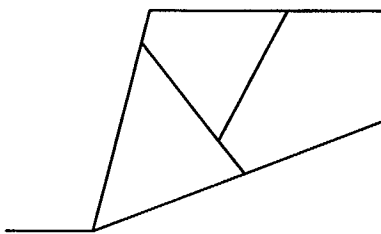
(d)



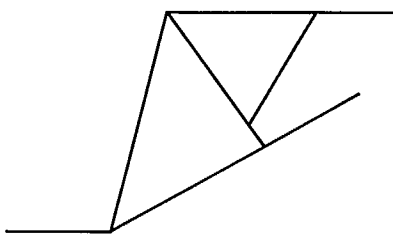
(e)



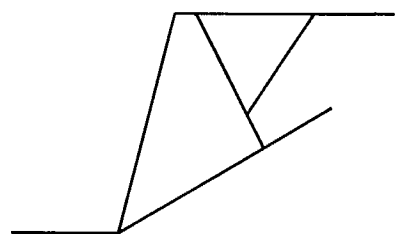
(f)



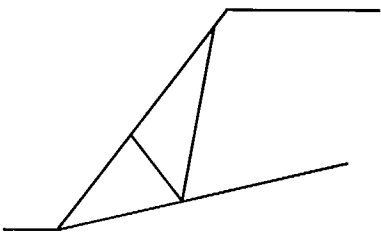
(g)



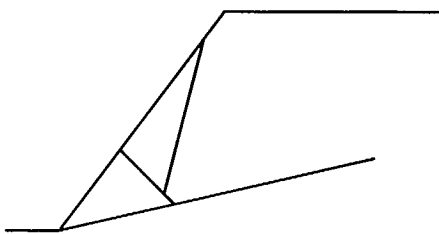
(h)



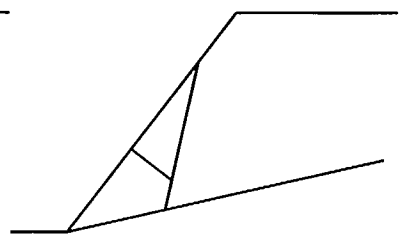
(i)



(j)

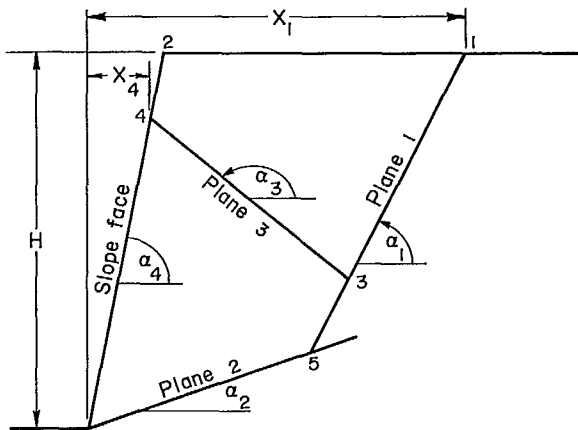


(k)



(1)

Fig B-1 - Possible two-block configurations.



- Note: (1) Top surface is assumed horizontal  
 (2)  $X_4$  is required only if the three shear surfaces do not intersect at a point

Fig B-2 - Parameters used to specify the two-block system.

$\alpha_2$  must be less than  $\phi_2$   
 ( $\phi_2$  = friction angle on plane 2);  
 plane 2 must daylight in the slope crest or face;  
 $\alpha_3$  must be greater than  $\alpha_1$ ; and  
 $\alpha_1$  must be less than  $90^\circ$ .

7. Three separate instances of the two-block instability mode can be defined for the program by means of the variable CONF as follows:  
 CONF = 1. Shear plane 1 terminates against shear plane 3 (Fig B-1g, h, i and k)  
 CONF = 2. Shear plane 3 terminates against shear plane 1 (Fig B-1a, b, c and e)  
 CONF = 3. or 4. All three shear planes meet at a point (Fig B-1d, e, f and j). In this case, the active wedge cannot move vertically down. It is, however, a convenient configuration to consider since it provides an extreme value for (WP/WA limiting). Both CONF = 3. and CONF = 4. define the same basic geometry but result in a difference in the joint sampling procedure of a probabilistic analysis.

#### Method of Solution

8. The two-block problem is analyzed by considering the vertical and horizontal equilibrium of the system. All the forces acting on the system shown in Fig B-3 can be determined at the condition of limiting equilibrium by assuming that full shear strength is mobilized on each plane, the directions of the resultants on the shear planes being known. Hence, for any

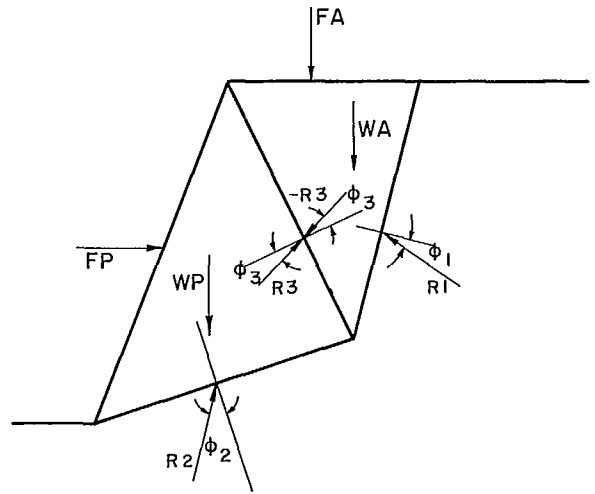


Fig B-3 - Forces acting on a two-block system at limiting equilibrium.

given weight of the active wedge, WA, the weight of the passive wedge which will create a state of limiting equilibrium, WP, can be determined. This enables the ratio (WP/WA limiting) to be calculated for a given geometry and for various friction angles.

9. The application of external forces to the active block affects the resultants acting on each shear plane. Cohesive and uplift forces are added to the frictional forces on the respective shear planes.

10. Externally applied loads on the active block are considered in two components, one vertical and one parallel to  $R_1$  (Fig B-4a). It is only the vertical component which affects  $R_3$ . External forces are assumed not to act on plane 3. An external force inclined in the direction of  $R_1$



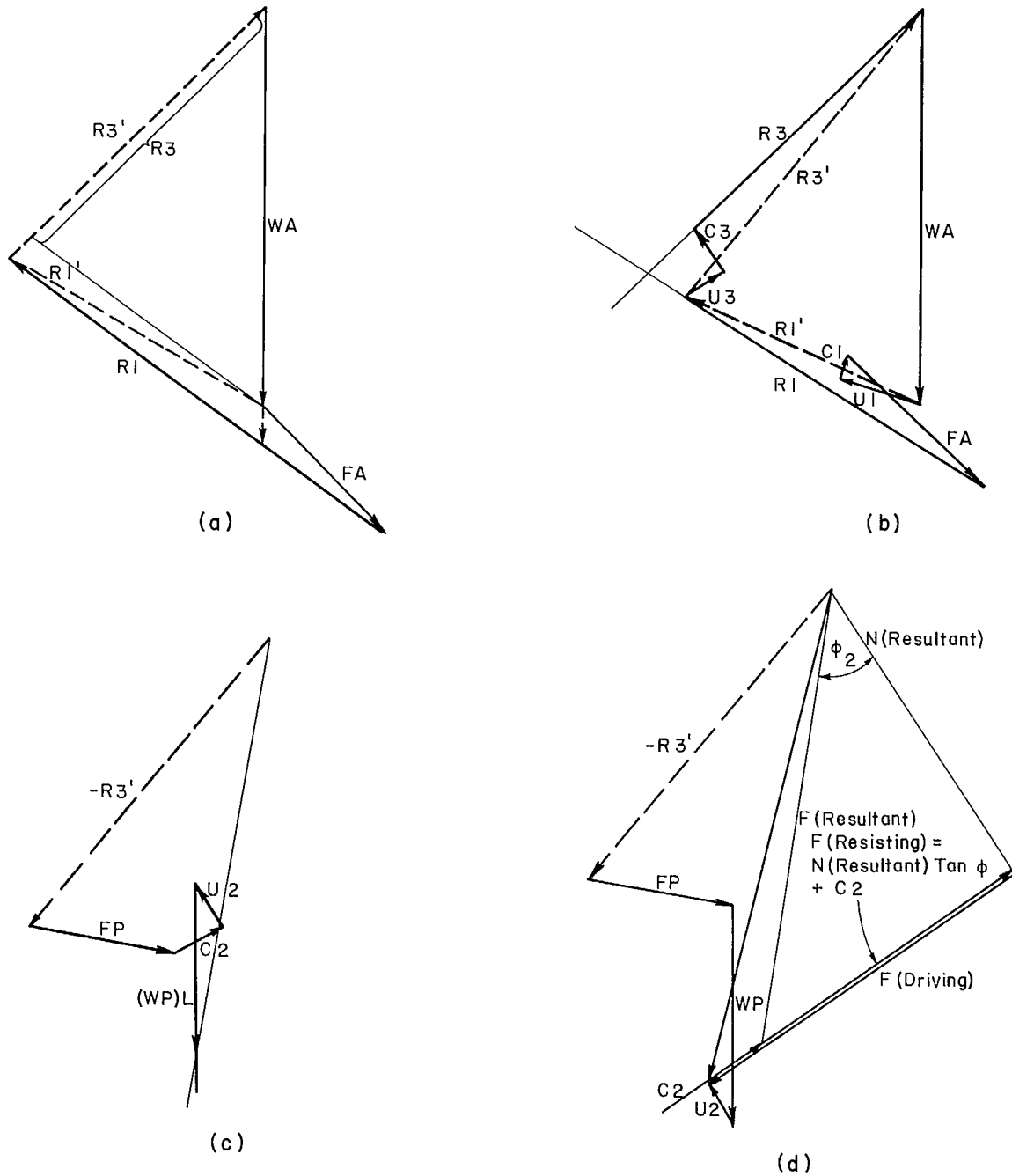


Fig B-4 - External forces in the two-block problem.

will have no effect on stability of the system. This is a somewhat arbitrary distribution of the applied force, but in practice it is not a serious limitation because loads applied to the active wedge will generally take the form of a surcharge directed vertically. The introduction of

additional assumptions to determine the forces on the active block will not usually be necessary.

11. The cohesive, uplift and external forces are combined as shown in Fig B-4b to give two resultant forces: the sum of all forces acting on plane 1,  $R1'$ , and the sum of all forces acting on

plane 3,  $R3'$ ; these define the magnitudes and directions of the forces acting on shear planes 1 and 3 when the active block is in limiting equilibrium. The assumption of limiting equilibrium of the active block is always made, and the principle of action-reaction enables the force transferred to the passive block to be taken as  $-R3'$ .

12. The passive block force polygon can now be solved for the condition of limiting equilibrium, using the known magnitude and direction of  $-R3'$ . The force applied externally to the passive block,  $FP$ , and the forces due to cohesion and uplift pressure on shear plane 2 can be added as shown in Fig B-4c. The force polygon must close, using the known directions of the weight and the friction force on plane 2 at  $\phi$  degrees from the normal. Thus the necessary weight of the passive block for it to be in a state of limiting equilibrium can be determined for calculating the stability factor.

13. For cases in which the weight of the blocks and friction are the only forces acting on the system, the limiting weight ratio of the active and passive blocks is conveniently calculated from the expression derived by Kuykendall and Goodman (B-1):

$$(WP/WA \text{ limiting}) = \frac{-\sin(\phi_1 - \alpha_1) \cdot \sin(\phi_3 + \alpha_3 + \phi_2 - \alpha_2)}{\sin(\phi_2 - \alpha_2) \cdot \sin(\phi_3 + \alpha_3 + \phi_1 - \alpha_1)}$$

14. When external forces act on the system, which in this context include cohesive and uplift forces, the limiting WP is determined from the force polygon. All resultant forces are calculated by summing external forces in the x and y directions and then closing the force polygons using the known directions of the friction forces. These values are determined within the program as:

$$R1 = [-F_{AX} \sin \theta_3 + (WA + F_{AY}) \cos \theta_3] / \sin(\theta_3 - \theta_1)$$

$$R3 = [F_{AX} \sin \theta_1 - (WA + F_{AY}) \cos \theta_1] / \sin(\theta_3 - \theta_1)$$

$$R2 = (R3 \cos \theta_3 - F_{PX}) / \cos \theta_2$$

where  $Ri$  = resultant of normal and frictional forces on plane  $i$ ,

$F_{ij}$  = sum of all forces excluding friction force acting on plane  $i$  in direction  $j$ , and

$\theta_i$  = the direction of the friction force on plane  $i$  measured clockwise from the positive x direction.

15. The weight of the passive block at limiting equilibrium is calculated as:

$$(WP \text{ limiting}) = R3 \sin \theta_3 - F_{PY} - R2 \sin \theta_2$$

16. The limiting weight ratio is then:

$$(WP/WA \text{ limiting}) = \frac{(WP \text{ limiting})}{WA}$$

The stability factor is calculated using the actual weight ratio of the active and passive blocks,  $(WP/WA)$ :

$$SF = (WP/WA) - (WP/WA \text{ limiting})$$

17. The stability factor is therefore zero at the condition of limiting equilibrium.

18. As an alternate measure of stability, the components of the forces acting on the passive block along shear plane 2 can be compared with the forces available to resist sliding in this direction, as shown in Fig B-4d, to determine a factor of safety. The transferred force,  $-R3'$ , the full weight of the passive block, external forces, and the water uplift force are summed to give a single resultant force acting on the passive block,  $F(\text{RESULTANT})$ . The total driving force is then determined as the component of  $F(\text{RESULTANT})$  acting along shear plane 2. The resisting force is the sum of the frictional shear strength due to the resultant normal force,  $N(\text{RESULTANT}) \tan \phi_2$ , and the cohesive shear strength on plane 2. The factor of safety is the total resisting force divided by the total driving force along this plane.

19. The following relationship between stability factor and factor of safety is used for the calculation of factor of safety:

$$FS = \frac{(WA \cos \alpha_2) (SF \tan \phi_2) + C_2 + R2 \sin \phi_2}{(WA \sin \alpha_2) SF + C_2 + R2 \sin \phi_2}$$

where  $\alpha_2$  = dip of plane 2,

$\phi_2$  = friction angle on plane 2,

$C_2$  = total cohesive force on plane 2, and

$R2$  = the reaction on plane 2.

20. The stability factor is a convenient measure to use when a simple two-block system is analyzed graphically. It is always computed by the program to provide a ready comparison with hand calculations. The more conventional factor of safety is used for all plotted output and the calculation of reliability. Its calculation by a direct count will give the same result, whichever measure of stability is used.

21. Some combinations of geometry and forces cannot be solved by this limiting equilibrium technique, even if the criteria of the two-block system are satisfied, because the criteria are only applied before the effects of external forces are considered. For instance, in Fig B-5a, the external forces acting on the active wedge combine with the weight of the active block to produce a resultant which acts at less than  $\phi_1$  degrees to the normal plane 1. Hence, the active block cannot be in a state of limiting equilibrium and the system does not constitute a valid two-block problem. Since the cohesive and uplift forces are considered as external forces, it is not always immediately apparent that a given geometry is not a valid two-block problem.

22. The example given in Fig B-5b shows a case in which, for a given force transferred from the active block,  $-R3'$  and external force,  $FP$ , the limiting equilibrium condition requires a negative reaction,  $R2$ , and a negative weight of the passive block. The first of these conditions arises because the external forces are acting upward

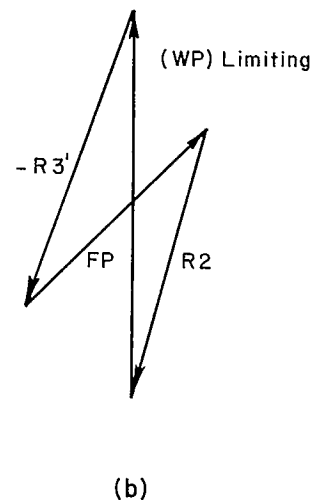
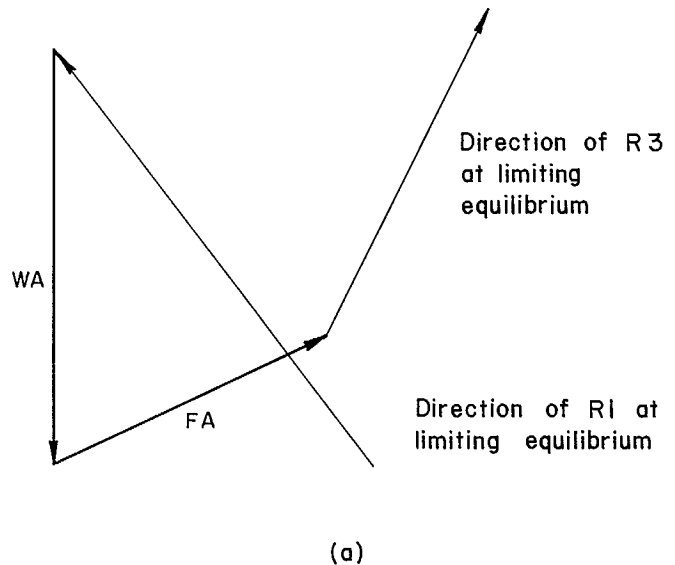


Fig B-5 - Force polygons of invalid two-block problems.

rather than downward on plane 2, and the second indicates that the weight of the passive block would have to act upwards, or be negative, for the limiting equilibrium condition to occur.

23. In the limiting case of one of the reaction forces on the active block being vertical, it

is assumed that the active block would remain stable on that plane, and so the problem is rejected as not being a valid case of the two block instability mode. Similarly, the example is also rejected if both reactions are vertical, in which case any distribution of forces would be arbitrary.

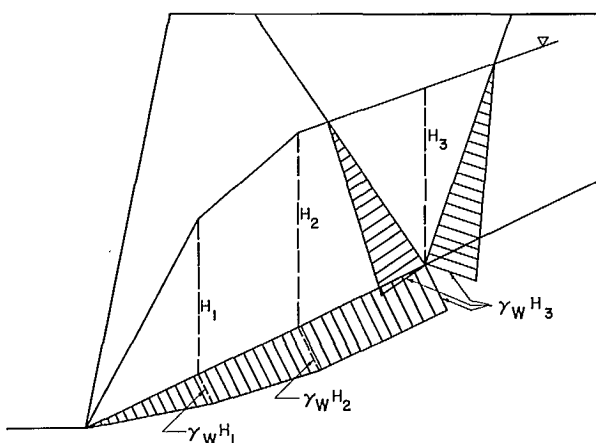
24. There is no facility for directly specifying a pseudo-static representation of an earthquake force. Modelling of earthquakes is complicated in the two-block problem by the uncertainty in representing most accurately the transfer of load from the active to the passive block and by the sensitivity of the analysis to the assumed direction of the transferred load. Simulating earthquake loading by applying assumed equivalent static forces to both active and passive blocks neglects the cyclic nature of earthquake loading and assumes that the maximum load is applied to both blocks simultaneously. This does provide, however, a method of indirectly considering earthquake loading.

25. Groundwater distribution is modelled by a linearly segmented piezometric line. Points on this line are specified by their x and y coordinates, with the origin at the toe of the slope. The piezometric line is always assumed to pass through

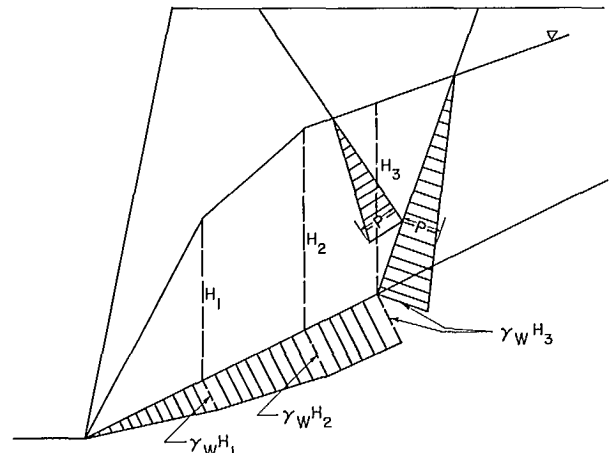
the toe of the slope, so this point need not be specified. The piezometric line should be permitted to cross each plane only once, otherwise an error in the calculated uplift forces will occur.

26. Water pressure on the lower shear plane, plane 2, is calculated from the height of the piezometric line above the sliding surface, and the total force due to water pressure is determined as the product of the pressure and the area over which it acts. When all three shear surfaces meet at a point, the water pressure along shear surfaces 1 and 3 is assumed to decrease linearly from the common intersection, to zero at the piezometric line, as shown in Fig B-6a. When all three shear surfaces do not intersect at a point, a linear decrease to zero pressure at the piezometric line is assumed from the intersection of planes 1 and 3, as shown in Fig B-6b and B6c.

27. Since the direction of movement of the passive block is along plane 2, the block is assumed to move away from any section of plane 1 or 3 which does not define part of the active block. The frictional and cohesive strengths of any such section are therefore assumed to be zero, and the force due to water pressure acting along this section is considered as a separate external

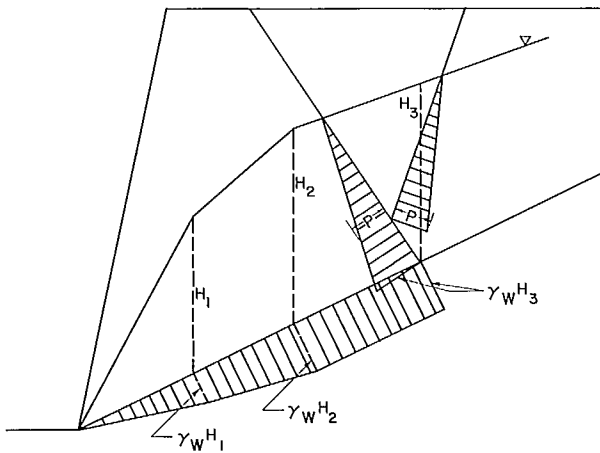


(a) All shear planes intersecting at a point



(b) Plane 3 terminates against plane 1

Fig B-6 - Assumed water pressure distributions in the two-block problem.



(c) Plane 1 terminates against plane 3

Fig B-6 (cont) - Assumed water pressure distributions in the two-block problem.

force.

28. When a sensitivity analysis is performed, the calculated stability factors and the varied parameters are stored in arrays for later printout. The sensitivity analysis is useful for evaluating the effect of different shear strength parameters. The location of the piezometric line cannot be varied automatically. No scaling of parameters is performed if any dimension of the system is varied in a sensitivity analysis. The user should consider the changes in geometry caused by altering the slope height or dip of the lower shear plane. He should be careful in varying the dip of the slope face lest the piezometric line fall outside the slope. To produce curves of reliability versus slope height, or slope angle, it may be necessary to redefine the slope geometry at each desired configuration, rather than to rely on the automatic sensitivity analysis to vary the slope geometry. The basic values of the parameters being varied must be included in the sensitivity analysis data if the stability factor and factors of safety for these values are to be computed, printed, and plotted.

29. When a probabilistic analysis is performed, all stochastic variables have gaussian, truncated gaussian, triangular, flat, or exponential distributions. All stochastic

variables, except the points defining the piezometric line, can also have a histogram-defined distribution. For a gaussian distribution, the sampling technique results in a cutoff of the sampled distributions at six standard deviations on either side of the mean. Truncated distributions should be used if it is required to limit the range of variables. All variables are considered independent.

30. When orientations of the shear planes are sampled for CONF = 1. or 2., the points at which the shear planes exit from the slope are defined first. These may be considered as deterministic or stochastic quantities, and the sampled shear planes are made to pass through these points as shown for case 1 in Fig B-7a.

31. For CONF = 3., the intersection point of planes 1 and 2 is calculated from the defined distributions of these planes, and plane 3 is then sampled so that it passes through this intersection point as shown in Fig B-7b.

32. For CONF = 4., the intersection of planes 2 and 3 is calculated from the defined distributions of these planes, and plane 1 is then sampled so that it passes through this intersection (Fig B-7c).

33. A series of checks is conducted on defined geometries to determine whether they constitute valid instances of the two-block mode. The number of cases found to violate each of these tests is printed out using the following error code system (see Fig B-2 for explanation of symbols):

TYPE A - checks for geometrical errors

Code	Error
1	$\text{ALPHA1} \geq 90^\circ$
2	$\text{ALPHA1} \geq \text{ALPHA3}$
3	$\text{ALPHA3} \geq 180^\circ$
4	$\text{ALPHA4} \geq \text{ALPHA2}$
5	Planes 1 and 3 intersect below plane 2
6	$X_1 \geq \frac{H}{\tan \text{ALPHA2}}$
7	$X_5 \leq 0$

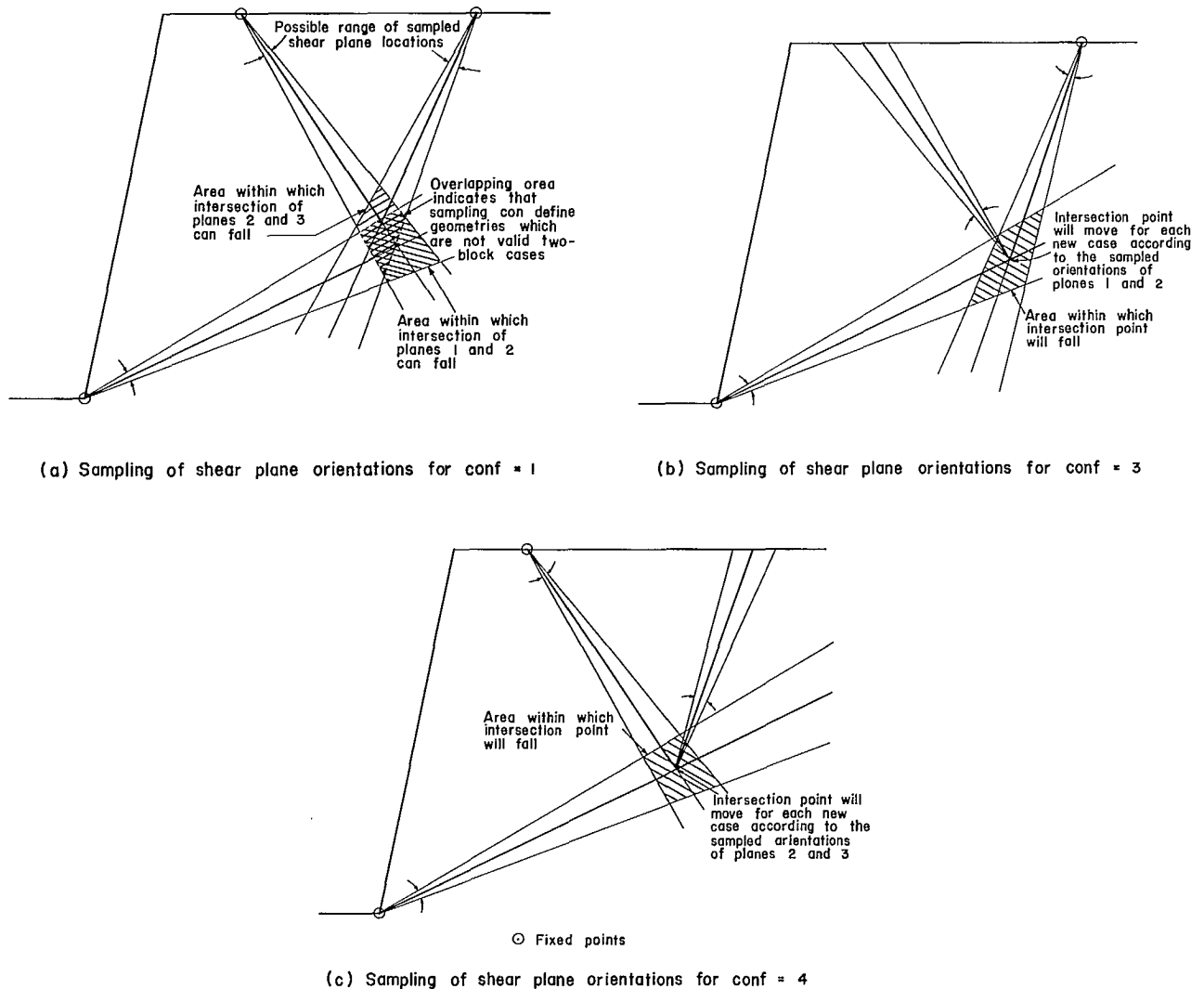


Fig B-7 - Sampling of shear plane orientations.

TYPE B - check that the active block is active

11  $\text{PHI1} \geq \text{ALPHA1}$  or  $\text{PHI3} \geq 180^\circ - \text{ALPHA3}$

TYPE C - check that the passive block is passive

12  $\text{PHI2} \leq \text{ALPHA2}$

34. The tests are conducted in the order specified above. Once an invalid case is defined, no more tests are conducted.

35. These tests are conducted before the effects of external forces are considered. If the external forces result in the active block being no longer active or the passive block being no

longer passive, these will not be reflected in the counts of invalid two-block problems. Instead, cases in which the passive block is not passive due to external forces will always be counted as unstable; cases where external forces result in an active block which is not active will be counted as stable, unless the passive block is inherently unstable.

36. No attempt is made to determine whether a system which does not constitute a two-block problem is a valid case of some other instability mode, such as simple plane shear. All non-valid cases are rejected, so the final probability

determined is that of instability in the two-block mode. This may not be the total probability of sliding.

37. In a deterministic run, the error code number is printed out and that particular analysis is terminated. The program then goes on to analyze any remaining cases that have been specified.

38. In a probabilistic run, the number of these errors is counted to determine the total number of invalid samples, and the number of invalid cases in each category is listed. In a detailed printout the error code will be printed for each invalid case. These cases are not included in the sample size used for determining reliability. The number of possible geometric configurations compels the user to be careful in specifying input distributions so that the results obtained truly represent the case being investigated. All cases considered should be drawn to scale with variations in sampling orientations and locations marked, as shown in Fig B-7, to avoid the sampling of unwanted cases.

39. The ideogram plot of the calculated factors of safety and the statistics associated with this distribution, including the estimate of reliability, refer only to the valid two-block cases. The distribution of the calculated factors of safety is plotted, and the mean, standard deviation, skewness, and kurtosis of these values are determined.

40. Reliability is defined as the probability of the factor of safety being less than that at limiting equilibrium; it is determined using one or both of the following techniques:

a. The normal distribution curve defined by the mean and standard deviation of the calculated factors of safety is assumed to be that of the population of factors of safety. Reliability is determined by evaluating the area under this

normal curve to the left of the limiting equilibrium condition. Using a distribution curve to represent the calculated results serves to smooth out the irregularities when the sample size is small.

b. A direct count is made of the factors of safety falling below the limiting equilibrium condition, from which reliability is determined as the percentage of the total population which these values represent. Besides simplicity, this method has the advantage that no assumptions need be made concerning the distribution of stability factors. For small sample sizes, up to 100 or so, there are irregularities associated with the Monte Carlo technique. For larger samples, the direct count gives a very reliable estimate of reliability. A sample size which gives 200 valid two-block cases should usually produce satisfactory results.

41. Marked differences in these two estimates may indicate either that the distribution is non-gaussian or that some input values are unacceptable. These inconsistencies must be explained and understood before the determined reliability can be accepted.

42. Any departure of the output distribution from normality will be reflected in the values of skewness and kurtosis. These values therefore give a useful indication as to the validity of assuming a normal distribution.

43. The Monte Carlo overlay, which is used to determine reliability, has been documented separately in Appendix E.

#### Flow Chart

44. Simplified flow charts for the various sections of the program are given in Fig B-8 through B-12. Appendix E gives details of the Monte Carlo overlay.

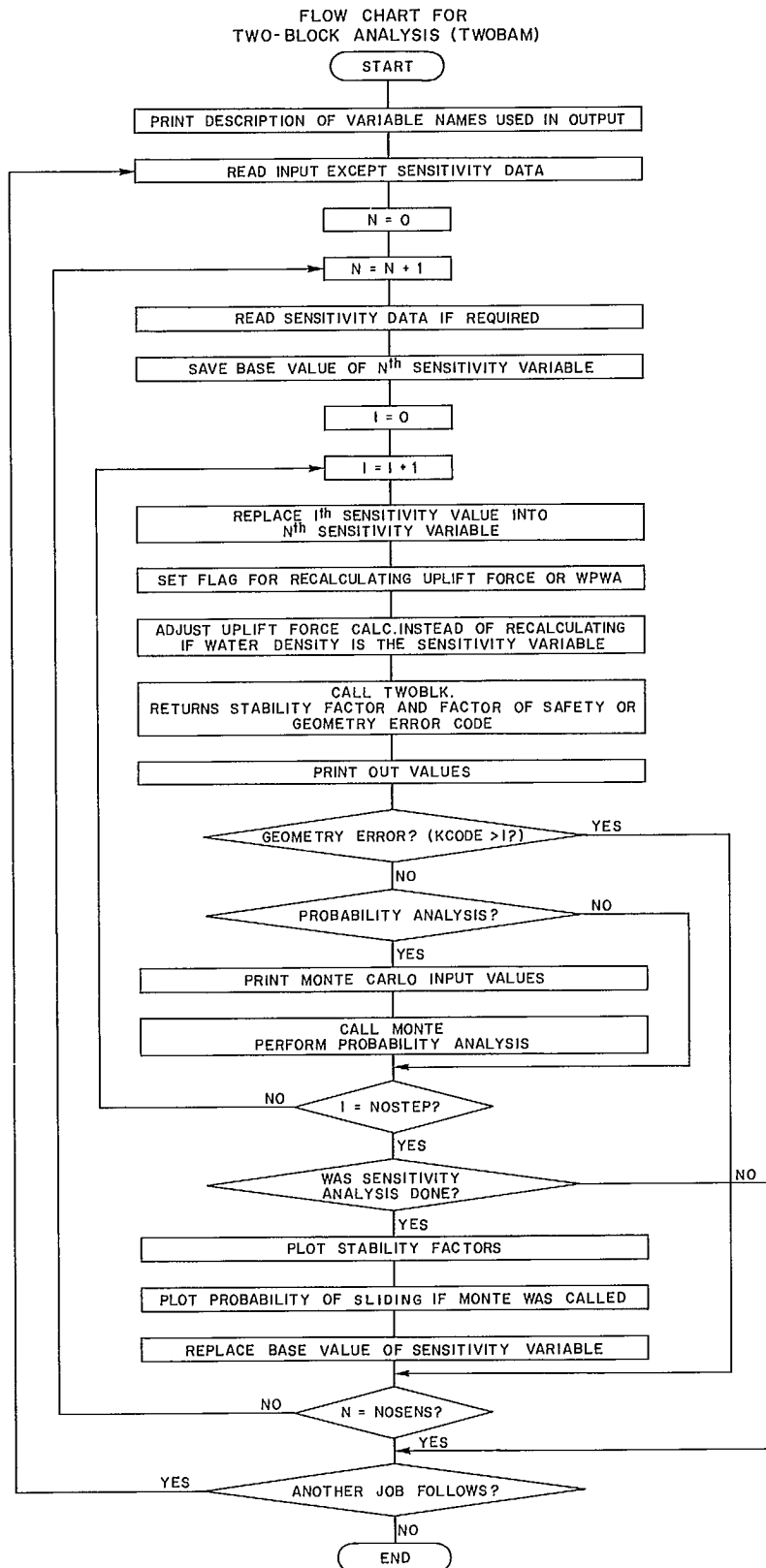


Fig B-8 - Flow chart for two-block computer analysis.



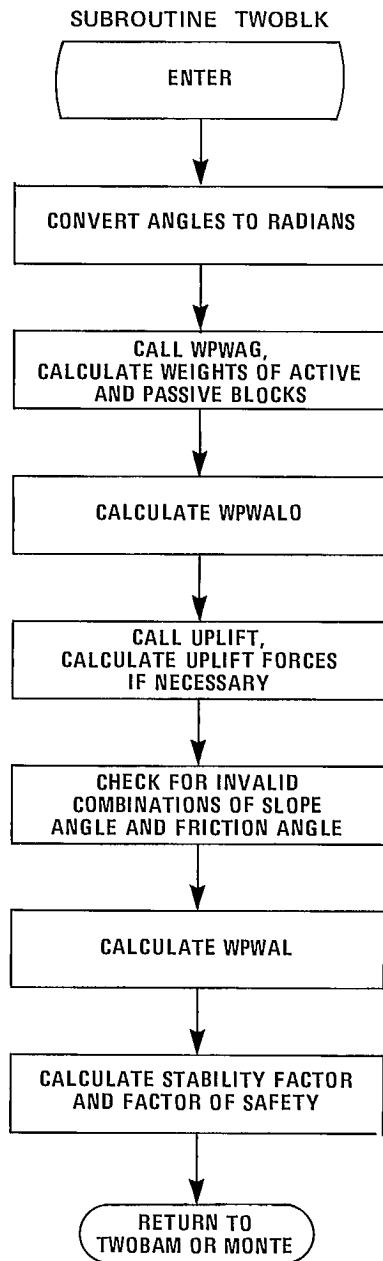


Fig B-9 - Flow chart for subroutine TWOBLK.

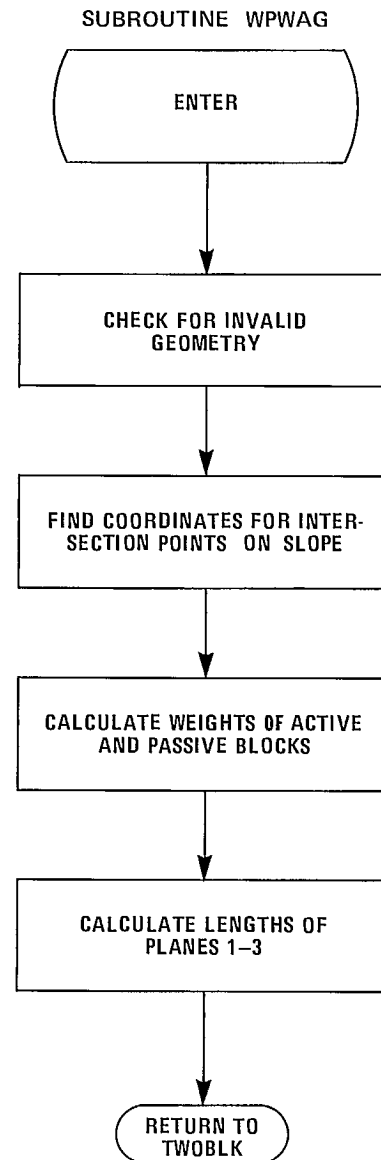


Fig B-10 - Flow chart for subroutine WPWAG.

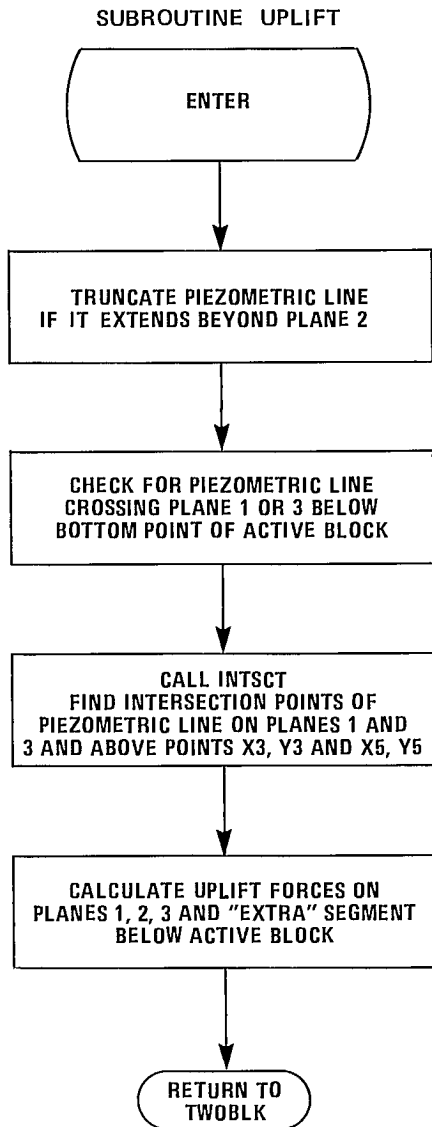


Fig B-11 - Flow chart for subroutine UPLIFT.

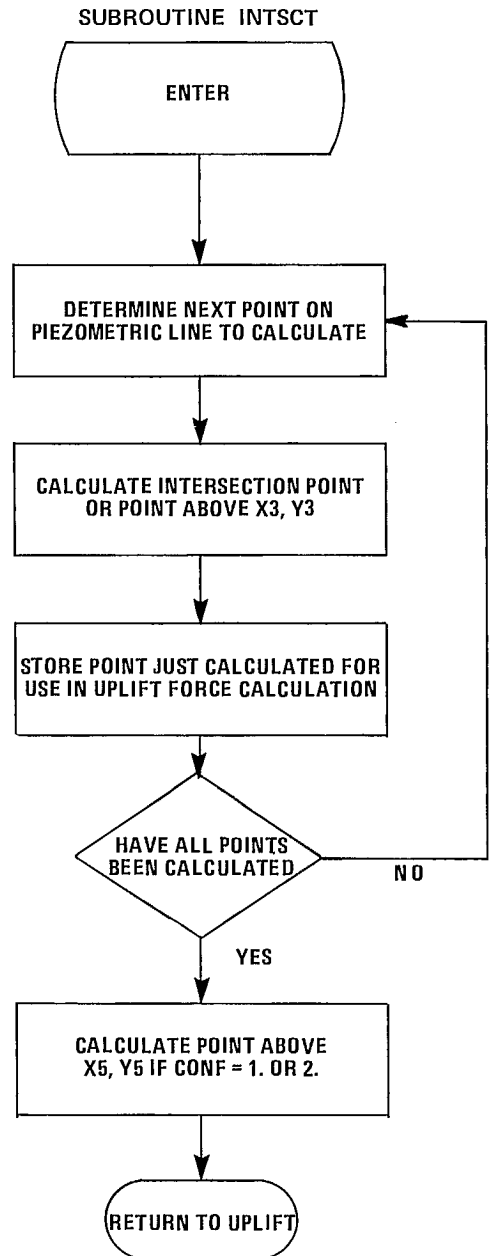


Fig B-12 - Flow chart for subroutine INTSCT.

## INPUT/OUTPUT

### Data Inputs

45. The meaning of input variables and the manner in which they are input are described in Exhibit B-1.

### Program Options

46. The available analysis options are described in Exhibit B-1.

### Printed Output

47. A description of variables used is always printed as the first page of output. The user can control the level of detail of printed output by specifying values of MPRT for a probabilistic analysis and PRINT for a sensitivity analysis as follows:

MPRT = 0. results in the printing of all the Monte Carlo input, the maximum and minimum calculated factors of safety, an ideogram plot of all calculated factors of safety, statistical data on this distribution, the calculated reliability and the number and type of invalid two-block cases sampled.

MPRT = 1. gives the output of the first option, plus a table of all calculated factors of safety

MPRT = 2. gives all the output of MPRT = 1. plus the sampled values of all variables and inter-

mediate calculations for every factor of safety calculation in the Monte Carlo analysis. This output is voluminous for large sample sizes.

PRINT = 0. gives the minimum printout for a sensitivity run. This includes plots of reliability and factor of safety against the parameter being varied in a probabilistic analysis, in addition to the output specified by MPRT, which is printed for each new sensitivity value. In a deterministic sensitivity analysis, it gives a printout of the basic input data, the values of the parameters being varied and a plot of the factor of safety against the parameter being varied.

PRINT = 1. gives additional printout of details of the intermediate steps in the stability calculation, using the basic data for a probabilistic analysis. In a deterministic analysis, this option results in the additional printout of the details of the intermediate steps, and both this and the entire input data are printed for each sensitivity step.

### Other Outputs

48. All output is produced on the line printer. No special messages other than those on the printed output are produced.

## SYSTEM AND OPERATING DOCUMENTATION

### Computer Equipment

49. The program was developed on a CDC 6600 and can therefore be run on any similar machine. The pseudo-random number generator exploits the word size of CDC equipment. It can be replaced by any of the pseudo-random number generators routinely available in all system libraries.

### Peripheral Equipment

50. Minimum peripheral equipment includes a card reader and a line printer.

### Operating Instructions

51. There are no special operating instructions for this program.

### Operating Messages

52. There are no special messages produced by the program.

### Control Cards

53. Standard compile and execute cards are all that are required to run the program.

### Error Recovery

54. Not applicable.

### Run Time

55. The sample problem took 13 CP seconds to run and cost about \$3.70.

### Data Structures

56. Not applicable.

### Storage Requirements

57. The program requires 42,000 octal words on the CDC 6600.

### Maintenance and Updates

58. Program development completed November, 1975. Histogram input added December 1976.

### Source Program

59. A listing of TWOBAM will be supplied with a card deck (card images on tape) at cost on request to Mining Research Laboratories, CANMET, Dept. of Energy, Mines and Resources, 555 Booth St., Ottawa K1A 0G1 Canada.

### Variables and Subroutines

60. Subroutines used are as follows:

TWOBAM - driver program for all analyses

DESCRIP - prints out description of variable names used in output

INPT - reads input data

TWOBLK - computes stability factor and factor of safety using other subroutines as appropriate

WPWAG - calculates weights of active and passive blocks, converts data to rectangular coordinates and checks for invalid geometries

UPLIFT - calculates uplift force on active and

passive blocks due to water pressure  
 INTSCT - calculates critical coordinates used in  
 uplift force calculation

OUT - prints output of deterministic analysis

OUTMON - prints output of probability analysis

FPLLOT - plots factors of safety from sensitivity  
 analysis

PLOT - plots probability of instability from sen-  
 sitivity analysis

MONTE - driver routine for probability analysis  
 subroutines

61. Additional subroutines used in the Monte  
 Carlo overlay have been documented separately.  
 Important variables used are listed below accord-  
 ing to the subroutine in which they are found.

#### TWOBAM:

ANCODE = analysis code (0. = deterministic, 1. =  
 probabilistic)

ANW = number of points on water line

BASE = base value of sensitivity variable

CONF = configuration code for slope geometry

FAC = adjustment factor for uplift force or water  
 line coordinates

ICLK = flag to recompute uplift force or WPWA

ISENS = index of sensitivity variable

KCODE = code for invalid cases

MODE = flag for new run

NAMEF = possible sensitivity variable names

NMSENS = number of different sensitivity variables

NSENS = number of loops on a given sensitivity  
 variable

PCODE = piezometric line sampling code (0. = de-  
 terministic, 1. = probabilistic)

PF = probability of instability array for sensi-  
 tivity plot

PRINT = print code for sensitivity analysis

FS = factor of safety array for sensitivity plot

SVAL = values of sensitivity variable

U = uplift force

VAR = slope parameter variables

XW = X coordinates of piezometric line

YW = Y coordinates of piezometric line

#### TWOBLK:

ALPS = slope angles in radians (from ALPHA)

ALPHA = slope angles in degrees

C = cohesive force along planes 1, 2 or 3

COH = cohesion

CONF = slope configuration code

COSA = cosines of ALPS

FA = external force on active block

FP = external force on passive block

FS = factor of safety of the passive block against  
 sliding on plane 2

ICLK = flag for calculating WPWA or uplift force

KCODE = code for invalid cases

NW = number of points on piezometric line

PHI = friction angles

PHIS = friction angles in radians

R = side forces on planes 1 through 3

RADIAN = conversion factor for degrees to radians

SF = stability factor

SINA = sines of ALPS

THETA = dip of external force on active block,  
 radians

THETAA = THETA in degrees

THETAP = THETP in degrees

THETAU = orientation of uplift force on passive  
 block, radians

THETP = dip of external force on passive block,  
 radians

U = uplift force

WA = weight of active block

WP = weight of passive block

WPWA = WP/WA

WPWAL = WPWA in the case of limiting stability

WPWALO = WPWAL assuming only frictional shear  
 force exists

X = X coordinates of various points on the slope

Y = Y coordinates of various points on the slope

XL = length of planes 1 - 3

#### WPWAG:

A1-A4 = same as ALPS array (see TWOBLK)

B1-B3 = Y intercept values for computing inter-  
 section points

CONF = slope configuration code

DENR = rock density

H = slope height

HPI =  $\pi/2$

KCODE = code for invalid cases

PI =  $\pi$

TT1-TT3 = saved values of T1 and T3 for CONF = 4.

T1-T4 = tangents of planes 1 - 4 corresponding to A1-A4

WA = weight of active block

WP = weight of passive block

XL = length of planes 1 - 3 and "extra" segment below active block (X3, Y3) - (X5, Y5)

X1-X5 = various X values of slope

Y1-Y5 = various Y values of slope

YC = point on plane 2 vertically below bottom point of active block

#### INLINE FUNCTIONS

A(X1,Y1,X2,Y2) = area under segment (X1,Y1), (X2,Y2)

RDIS(X1,Y1,X2,Y2) = distance of segment (X1,Y1), (X2,Y2)

#### UPLIFT

B = Y intercept

CONF = slope configuration code

DENW = water density

IC = critical points on piezometric line for uplift force calculation

IFLG = flag for water line position in relation to active block

NW = number of points on piezometric line after calculating crossing points

N1 = second point on piezometric line for uplift calculation

N2 = last point on piezometric line for uplift calculation

SL = slope of piezometric line segments

TA = tangents of slope angles

U = uplift force

XF = check for piezometric line beyond plane 2

XW = X coordinates of points on piezometric line

YW = Y coordinates of points on piezometric line

#### INTSCT:

ALPHA = angles of planes 1-4

B1, B2 = Y intercept values

CONF = slope configuration code

IADD = extra points added on piezometric line after finding point above X5, Y5

IC = points where piezometric line crosses planes 1 and 3 and points above X3, Y3 and X5, Y5

NEXT = next intersection point to calculate

NW = number of points on piezometric line including critical points defined in IC

SL1, SL2 = slope angles

#### SAMPLE PROBLEM

62. A slope 100 ft (30 m) high (H) lies in competent rock in which are two distinct joint sets dipping into the pit, one at 60 degrees and the other at 30. A fault is intersected which dips into the slope at an angle of 45 degrees. At the proposed location of the ultimate slope, the combination of the joints and fault will give the potential two-block configuration shown in Fig B-13, where the piezometric data has been extrapolated from measurements in the present slope. The effect of an impermeable fault zone on the water distribution in the slope is not considered at this stage.

63. The characteristics of the three potential shear planes are defined by a geological investigation as follows:

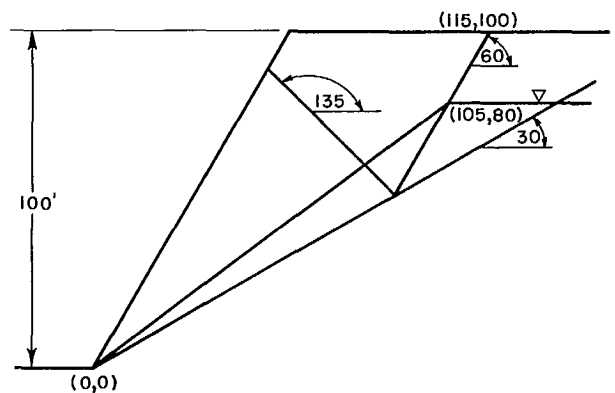


Fig B-13 - Two-block sample problem.

Characteristics	Set 1
Mean dip	60 (ALPHA1)
Standard deviation	4
Mean friction angle	35 (PH1)
Standard deviation	3
Mean cohesion	500 lb/ft <sup>2</sup> (COH1) (23.9 kPa)
Standard deviation	150 lb/ft <sup>2</sup> (7.18 kPa)

	Set 2
Mean dip	30 (ALPHA2)
Standard deviation	4
Mean friction angle	37 (PHI2)
Standard deviation	3
Mean cohesion	1000 lb/ft <sup>2</sup> (COH2) (47.9 kPa)
Standard deviation	200 lb/ft <sup>2</sup> (9.5B kPa)

	Set 3
Mean dip	45 (ALPHA3=135)
Standard deviation	3
Mean friction angle	15 (PHI3)
Standard deviation	2
Mean cohesion	200 lb/ft <sup>2</sup> (COH3) (9.58 kPa)
Standard deviation	100 lb/ft <sup>2</sup> (4.78 kPa)

64. The density of the rock (DENR) has a mean of 160 lb/ft<sup>3</sup> (2.56 t/m<sup>3</sup>) and a standard deviation of 5 lb/ft<sup>3</sup> (0.08 t/m<sup>3</sup>). The problem is to determine the probability of two-block instability.

### Procedure

65. Input data for the solution of this problem are given in Fig B-14. After using the Header (A) card for an appropriate job description, the Control (B) card is used to specify a probabilistic analysis (CALCS = 1.). The piezometric line is defined by a single point (NW = 1.) the location of which is specified probabilistically (CODEC = 1.). One input parameter will be varied in a sensitivity analysis (NOSENS = 1.).

66. The basic problem is defined on the C, D and E cards. The distance from the toe of the slope to the exit point of plane 1 (X1 = 115.) is defined, but the distance to the exit point of plane 3 (X4) is left blank because this distance is calculated by the program for the slope configuration defined (CONF = 3.). Since no external forces act on the system, the relevant parameters on the E card (FA, THETAA, FP, THETAP) are left blank or entered as zeros.

67. The Piezometric Line Definition (F) card is used to specify the coordinates of the point on the piezometric line (XW(1) = 105., YW(1) = 80.), with the origin at the toe of the slope, and the piezometric line to the right of the last specified point is assumed horizontal. Only one F card is therefore required.

68. Since a probabilistic analysis is being performed, the Probabilistic Analysis Control (G) card is used to specify the sample size for each stability analysis (NSAMPL = 200.), the starting number for the random number generator (MF = 123.), and a printout which gives an ideogram plot and a table of calculated factors of safety (MPRT = 1.). It also gives the height in terms of the number of characters of the ideogram plot (NX = 80.), the number of class intervals of the plot (BINSIZ = 20.), and the total number of parameters which are to be considered stochastic, rather than deterministic, variables (NSTV = 10.).

## 2641930000GM 122275 TWO-BLOCK SAMPLE CASE PROBABILISTIC ANALYSIS

1.	1.	1.	1.		
60.	30.	135.	60.	100.	115.
35.	37.	15.	500.	1000.	200.
160.	62.4				3.
105.	80.				
200.	123.	1.	80.	10.	20.
1.	1.	4.			
2.	1.	4.			
3.	1.	3.			
3.	1.	3.			
9.	1.	3.			
10.	1.	2.			
11.	4.	150.	500.	900.	
12.	4.	200.	1000.	1200.	
13.	4.	100.	200.	600.	
14.	1.	5.			
2.					
10.	10.				
10.	3.	1.			
10.	15.	20.			

0.

Fig B-14 - Input data for sample problem.

69. The following ten (H) cards are used to define the distributions of the ten stochastic variables according to the index numbers of the parameters, the Distribution Definition Code, and the Variable Distribution Definitions. For instance, the dip of shear plane, (STV = 1.) is defined to be normally distributed (TYPE = 1.) with a standard deviation of four degrees (ST1 = 4.), the mean being taken as the value defined on the Basic Input Data cards. Because of their large variances, the cohesions (STV = 11., 12. and 13.) are defined as truncated normal distributions (TYPE = 4.) to ensure there is no sampling of negative values.

70. The I card defines the distribution of the defined point on the water line as being triangular (TYPEW = 2.), and the J card defines the distances to the limits of the distribution from the value input on the Basic Input Data cards (STW1 = 10., STW2 = 10.).

71. To investigate the sensitivity of the stability of the system to the shear strength of the fault, PHI3 is varied (NVAR = 10.) in three steps (NOSTEP = 3.), and details of the calculations at each step are to be printed out (PRINT = 1.). This is all specified on the Sensitivity Analysis Control (K) card. The Sensitivity Analysis Data (L) card is used to

specify the three values which PHI3 is to take (10. 15. and 20.), and this includes the value PHI3 specified in the Basic Input Data.

72. Finally, the Continuation Control (M) card is used to specify that the analysis has been completed (NEXT = 0.).

73. The output generated (see Exhibit B-2), consists initially of a description of all variables which appear in the output. The heading is then printed, followed by the basic input data, and the coordinates of the points which define the piezometric line. As the toe of the slope is listed as one of these points, their number is one more than the value of NW input.

74. Results of intermediate steps in calculating stability for the base data case, ie, lengths, forces, weights, etc., are printed out where the variable names comply with the descriptions given on the first page of the output. This includes the calculated stability factor (SF) and factor of safety (FS) for the base case.

75. The probabilistic analysis data is printed. This includes the distributions defined for all input variables using the same stochastic variable definition codes as on the load sheet. This is followed by a table of all the factors of safety calculated in the Monte Carlo process.



76. An ideogram plot of the frequency distribution of calculated factors of safety is produced, along with the sample statistics of these values.

77. The final printout for the first slope is the reliability as estimated, both by a direct count of the factors of safety falling below 1.0, and by determining the probability of the factor of safety falling below 1.0, assuming the calculated factors of safety to be normally distributed. It should be noted that these probabilities refer to the probability of a two-block instability occurring for the number of cases in which a valid two-block problem is

defined, since the specified sample size (NSAMPL) is reduced by the number of sampled cases which are not valid two-block problems. The number of samples which fall into each category of non-valid two-block problems are listed with the estimated reliabilities.

78. The printout from the heading and basic input information to the reliability calculation are repeated for each new parameter value specified in the sensitivity analysis. This is followed by a plot of factor of safety against the parameter varied in the sensitivity analysis, with all other parameters retained at their original base values.



**EXHIBIT B-1**



## DATA INPUT

### DATA INPUT FOR TWOBAM

#### A. Header card - Format (A10,A3,A6,6A10)

Job number  
User's initials  
Date  
Title

#### B. Control card - Format (4F10.0)

Calcs - Analysis code

0. = deterministic

1. = probabilistic

NW - number of points defining piezometric line  
(maximum 19)

CODEC - Piezometric line sampling code

0. = deterministic

1. = probabilistic

NOSENS - number of different variables for  
sensitivity analysis

#### C. Slope geometry - Format (7F10.0) (see Fig B-15 - numbers in parentheses are index numbers of the variables)

ALPHA1 (1)

ALPHA2 (2)

ALPHA3 (3)

ALPHA4 (4)

H (5)

X1 (6)

X4 (7)

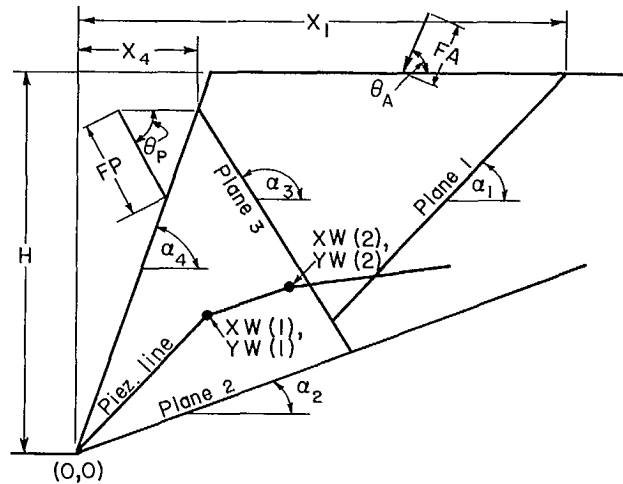


Fig B-15 - Definition of input variables for two-block problem.

#### D. Shear strength parameters - Format (6F10.0) (numbers in parentheses are index numbers of the variables)

PHI1 (8) - friction angle for plane 1

PHI2 (9) - friction angle for plane 2

PHI3 (10) - friction angle for plane 3

COH1 (11) - cohesion on plane 1

COH2 (12) - cohesion on plane 2

COH3 (13) - cohesion on plane 3

#### E. Unit weights, external forces and geometry - Format (6F10.0) (numbers in parentheses are

index numbers of the variables)

DENR (14)- unit weight of rock

DENW (15)- unit weight of water

FA (16)- Force on active block, Fig B-15

THETAA (17) - dip of force on active block,  
Fig B-15

FP (18)- Force on passive block,  
Fig B-15

THETAP (19) - dip of force on passive block,  
Fig B-15

CONF - configuration code, Fig B-16

F. Piezometric line definition - Format 8F10.0.  
(NW pairs required at 4 pairs per card, maximum  
5 cards - skip if NW = 0. on card B)

XW(1)

YW(1)

XW(2)

YW(2)

.

.

.

XW(19)

YW(19)

G. Probabilistic analysis control card - Format  
(6F10.0) (Skip cards G, H, I and J if CALCS =  
0. on card B)

NSAMPL - number of samples required for Monte  
Carlo analysis

MF - first seed for random number generator

MPRT - print code

0. = print input data and results of statis-  
tical analysis

1. = as 0. plus stability factor table

2. = as 1. plus calculation details of each  
valid two-block system

NX - number of characters in output ideogram

NSTV - number of stochastic variables

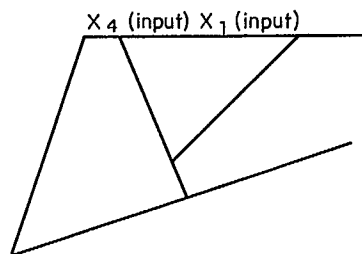
BINSIZ - ideogram control

<1. = class interval for ideogram

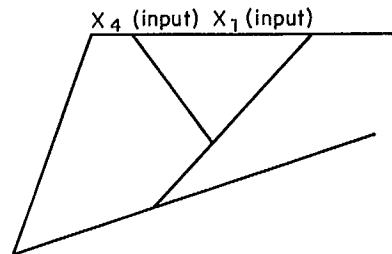
>1. = number of classes

H. Stochastic variable definition cards - Format  
(F3.0,F2.0,3F10.0,9F5.0) (NSTV cards, each as  
described)

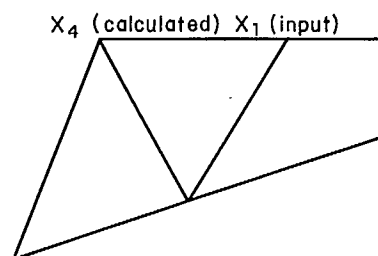
STV - index number of stochastic variable (see  
cards C, D and F)



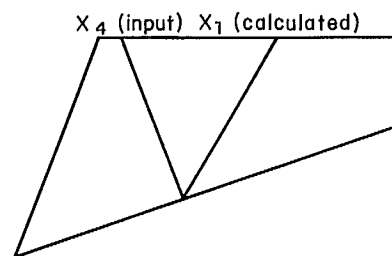
Conf = 1



Conf = 2



Conf = 3



Conf = 4

Fig B-16 - Slope configurations identified by variable CONF.

TYPE - distribution control (see Figs B-16, B-17)

ST1 } distribution  
ST2 } parameters  
ST3 } Fig B-17 if  $1. \leq \text{TYPE} \leq 5$ .  
ST4 (I), I=1,9 } Fig B-18 if TYPE = 6.

I. Distribution control for piezometric line - Format (F10.0) (skip cards I and J if piezometric line is deterministic)

TYPEW - distribution control - as TYPE on cards

H except restricted to range 1 through

5

J. Dispersion definition for piezometric line - Format (3F10.0) (NW cards - see card B - each card as described)

STW1 } as ST1, ST2, ST3 on cards H -  
STW2 } Fig B-17  
STW3 } (Fig B-18 does not apply)

K. Sensitivity analysis control - Format (3F10.0) (repeat cards K and L as a group NOSENS times, ie, for each sensitivity variable, see card B)  
NVAR - index number of variable - see card C-E  
NOSTEP - number of different values (entered on card L) for variable NVAR; must be  $\geq 2$ .

PRINT - print control - Format (F10.0)

0. = input and final plot only printed

1. = as 0. plus intermediate calculations for each step

L. Sensitivity analysis values - NOSTEP values at 8 per card (maximum 40 values - 5 cards) - Format (8F10.0) SVAL(I), I = 1, NOSTEP

M. Continuation control - Format (F10.0)

NEXT = 0. Stop job

= 1. another job follows - go to card A.

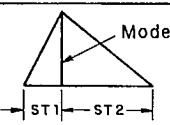
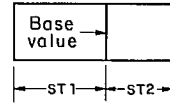
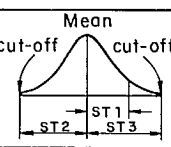
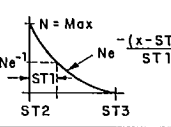
TYPE	ST 1	ST 2	ST 3
1.	Standard deviation	blank	blank
2.	Maximum distance from the mode to the left (lower) side (positive distance)	Maximum distance from the mode to the right (upper) side.	blank 
3.	Maximum distance from the base input value to the left (lower) side (positive distance)	Maximum distance from the base input value to the right (upper) side	blank 
4.	Standard deviation 	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side.
5.	Decay constant 	Lower bound Measured from 0	Upper bound Measured from 0

Fig B-17 - Definition of stochastic variables.

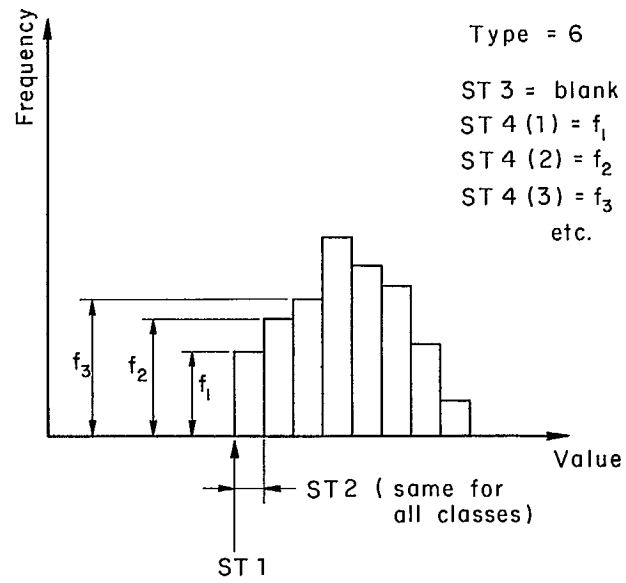


Fig B-18 - Definition of histogram input.



EXHIBIT B-2

OUTPUT



## DESCRIPTION OF VARIABLES USED IN OUTPUT TABLE

ALPHA1 = ANGLE OF ACTIVE BLOCK SLIDING PLANE(DEG)  
 ALPHA2 = ANGLE OF PASSIVE BLOCK SLIDING PLANE(DEG)  
 ALPHA3 = ANGLE OF PASSIVE-ACTIVE INTERFACE(DEG)  
 ALPHA4 = ANGLE OF SLOPE FACE(DEG)  
 H = SLOPE HEIGHT  
 PHI1 = FRICTION ANGLE ON ACTIVE BLOCK SLIDING PLANE(DEG)  
 PHI2 = FRICTION ANGLE ON PASSIVE BLOCK SLIDING PLANE(DEG)  
 PHI3 = FRICTION ANGLE ON PASSIVE-ACTIVE INTERFACE(DEG)  
 COH1 = COHESION ON ACTIVE BLOCK SLIDING PLANE  
 COH2 = COHESION ON PASSIVE BLOCK SLIDING PLANE  
 COH3 = COHESION ON PASSIVE-ACTIVE INTERFACE  
 DENR = UNIT WEIGHT OF ROCK  
 DENW = UNIT WEIGHT OF WATER  
 FA = EXTERNAL FORCE ON THE ACTIVE BLOCK  
 THETAFA = ORIENTATION OF FA FROM HORIZONTAL  
 FP = EXTERNAL FORCE ON THE PASSIVE BLOCK  
 THETAFP = ORIENTATION OF FP FROM HORIZONTAL  
 CONF = SLOPE GEOMETRY CONFIGURATION CODE  
 NW = NUMBER OF WATER LINE POINTS  
 XW(I) = HORIZONTAL COORDINATE OF POINT I ON THE WATER LINE  
 YW(I) = VERTICAL COORDINATE OF POINT I ON THE WATER LINE  
 X1,Y1 = COORDINATES OF ACTIVE BLOCK SLIDING PLANE AT THE SURFACE  
 X2,Y2 = COORDINATES OF THE TOP OF THE FACE  
 X3,Y3 = COORDINATES OF THE BOTTOM POINT OF THE ACTIVE BLOCK  
 X4,Y4 = COORDINATES OF THE PASSIVE-ACTIVE INTERFACE AT THE SURFACE  
 X5,Y5 = COORDINATES OF THE RIGHTMOST POINT OF THE PASSIVE BLOCK SLIDING PLANE  
 XL1 = LENGTH OF SEGMENT FROM (X1,Y1) TO (X3,Y3)  
 XL2 = LENGTH OF SEGMENT FROM (0.,0.) TO (X3,Y3)  
 XL3 = LENGTH OF SEGMENT FROM (X3,Y3) TO (X4,Y4)  
 XL4 = LENGTH OF SEGMENT FROM (X3,Y3) TO (X5,Y5)  
 VA = VOLUME OF THE ACTIVE BLOCK  
 VP = VOLUME OF THE PASSIVE BLOCK  
 WA = WEIGHT OF THE ACTIVE BLOCK  
 WP = WEIGHT OF THE PASSIVE BLOCK  
 WPL = WEIGHT OF THE PASSIVE BLOCK AT LIMITING EQUILIBRIUM  
 WPGA = WP/WA  
 WPGALO = WPGA WITH ORIGINAL FRICTION ANGLES  
 WPGAL = WPGA IN THE LIMITING CASE  
 U1 = UPLIFT FORCE ALONG SEGMENT XL1  
 U2 = UPLIFT FORCE ALONG SEGMENT XL2  
 U3 = UPLIFT FORCE ALONG SEGMENT XL3  
 U4 = UPLIFT FORCE ALONG SEGMENT XL4  
 C1 = COHESIVE FORCE ON PLANE 1  
 C2 = COHESIVE FORCE ON PLANE 2  
 C3 = COHESIVE FORCE ON PLANE 3  
 R1 = SIDE FORCE ON PLANE 1  
 R2 = SIDE FORCE ON PLANE 2  
 R3 = SIDE FORCE ON PLANE 3  
 FA = EXTERNAL FORCE ON ACTIVE BLOCK  
 FP = EXTERNAL FORCE ON PASSIVE BLOCK  
 FXONA = X-COMPONENT OF RESULTANT OF FA+C1+U1+C3+U3+WA  
 FYONA = Y-COMPONENT OF RESULTANT OF FA+C1+U1+C3+U3+WA  
 FXONP = X-COMPONENT OF RESULTANT OF FP+C2+U2-C3-U3  
 FYONP = Y-COMPONENT OF RESULTANT OF FP+C2+U2-C3-U3  
 F2T = DRIVING FORCE ON PLANE 2  
 F2N = EFFECTIVE NORMAL FORCE ON PLANE 2  
 SF = STABILITY FACTOR (WPGA-WPGALF)  
 FS = FACTOR OF SAFETY OF PASSIVE BLOCK AGAINST SLIDING ON PLANE 2  
 ST1 = STANDARD DEVIATION FOR GAUSSIAN DISTRIBUTION,  
 LOWER LIMIT FROM BASE FOR TRIANGULAR OR UNIFORM  
 ST2 = UPPER LIMIT FROM BASE FOR TRIANGULAR OR UNIFORM DISTRIBUTION  
 LOWER CUT-OFF VALUE FOR TRUNCATED GAUSSIAN DISTRIBUTION  
 ST3 = RIGHT CUT-OFF VALUE FOR TRUNCATED GAUSSIAN DISTRIBUTION  
 ST4 = ARRAY OF RELATIVE FREQUENCIES FOR HISTOGRAM DISTRIBUTION (UP TO 9 VALUES)  
 STW1-I = LOWER LIMIT FROM BASE FOR TRIANGULAR OR UNIFORM DISTRIBUTION ON WATER LINE POINT I,  
 STANDARD DEVIATION FOR GAUSSIAN DISTRIBUTION  
 STW2-I = UPPER LIMIT FROM BASE FOR TRIANGULAR OR UNIFORM DISTRIBUTION ON WATER LINE POINT I,  
 LOWER CUT-OFF VALUE FOR TRUNCATED GAUSSIAN DISTRIBUTION  
 STW3-I = UPPER CUT-OFF POINT FOR TRUNCATED GAUSSIAN DISTRIBUTION

## TWO-BLOCK SAMPLE CASE PROBABILISTIC ANALYSIS

SEE DESCRIPTION OF VARIABLES ON FIRST PAGE OF OUTPUT

\*\*\*\*\*  
INPUT DATA  
\*\*\*\*\*

ALPHA1 60.0	ALPHA2 30.0	ALPHA3 143.0	ALPHA4 60.0	H 100.0	X1 115.0	X4 -0.0
PHI1 35.0	PHI2 37.0	PHI3* 10.0				
CCH1 500.0	COH2 1000.0	COH3 200.0	DENR 160.0	DENH 62.4		
FA -0.0	THETAA -0.0	FP -0.0	THETAP -0.0	CDHF 3.0	NH 2.0	

POINTS ON PIEZOMETRIC LINE

PT. NO.	1	2
XM	0.00	105.00
YM	0.00	80.00

\*\*\*\*\*  
OUTPUT  
\*\*\*\*\*

X1 115.00	Y1 100.00	X2 57.74	Y2 100.00	X3 85.90	Y3 49.59	X4 45.98	Y4 79.65	X5 85.90	Y5 49.59	VP 2200.44	VA 2026.09
XL1 58.21	XL2 99.19	XL3 49.96	XL4 0.00	U1 16164.3	U2 45057.9	U3 6479.2	U4 0.0	C1 29102.5	C2 99185.0	C3 9992.6	
R1 157068.4	R2 36587.6	R3 154119.6	FXOA -3533.1	FYQHA 279702.3	WA 324174.5	FXONP 65454.2	FYONP -80891.8	HPL -20143.2	HP 364870.1	F2T 313711.5	F2N 322651.5
MPHA 1.13	MPHAL0 1.50	MPHAL -0.0E	SF 1.19	FS 1.19							

\* - SENSITIVITY ANALYSIS WAS DONE ON THIS VARIABLE

\*\*\*\*\*  
PROBABILITY ANALYSIS - DETAIL OF INPUT  
\*\*\*\*\*

ND. OF SAMPLES	1ST RAND NO.	SEED	PRINT CODE	GRAPH SIZE	STAT VOLS	ND. OF CLASSES
200.	123.		1.	80.	10.	20.000

RANGE AND TYPE OF DISTRIBUTION USED  
TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = TRUNCATED GAUSSIAN, TYPE5 = EXPONENTIAL  
TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING DONE

VARIABLE	ALPHA1	ALPHA2	ALPHA3	ALPHA4	H	X1	X4
BASE	60.00	30.00	143.02	60.00	100.00	115.00	-0.00
TYPE	1	1	6	0	0	0	0
ST1	4.00	4.00	135.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	2.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	-0.00	0.00	0.00	0.00	0.00
H	-0.00	-0.00	1.00	-0.00	-0.00	-0.00	-0.00
I V	-0.00	-0.00	3.00	-0.00	-0.00	-0.00	-0.00
S A	-0.00	-0.00	9.00	-0.00	-0.00	-0.00	-0.00
T L	-0.00	-0.00	11.00	-0.00	-0.00	-0.00	-0.00
O U	-0.00	-0.00	8.00	-0.00	-0.00	-0.00	-0.00
G E	-0.00	-0.00	5.00	-0.00	-0.00	-0.00	-0.00
R S	-0.00	-0.00	3.00	-0.00	-0.00	-0.00	-0.00
A	-0.00	-0.00	2.00	-0.00	-0.00	-0.00	-0.00
M	-0.00	-0.00	1.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	PHI1	PHI2	PHI3	CDH1	CDH2	COH3
BASE	35.00	37.00	10.00	500.00	1000.00	200.00
TYPE	1	1	1	4	4	4
ST1	3.00	3.00	2.00	150.00	200.00	100.00
ST2	0.00	0.00	0.00	500.00	1000.00	200.00
ST3	0.00	0.00	0.00	900.00	1200.00	600.00
H	-0.00	-0.00	-0.00	0.00	0.00	0.00
I V	-0.00	-0.00	-0.00	0.00	0.00	0.00
S A	-0.00	-0.00	-0.00	0.00	0.00	0.00
T L	-0.00	-0.00	-0.00	0.00	0.00	0.00
O U	-0.00	-0.00	-0.00	0.00	0.00	0.00
G E	-0.00	-0.00	-0.00	0.00	0.00	0.00
R S	-0.00	-0.00	-0.00	0.00	0.00	0.00
A	-0.00	-0.00	-0.00	0.00	0.00	0.00
M	-0.00	-0.00	-0.00	0.00	0.00	0.00

VARIABLE	DENR	DENH	FA	THETAA	FP	THETAP
BASE	160.00	62.40	-0.00	-0.00	-0.00	-0.00
TYPE	1	0	0	0	0	0
ST1	5.00	0.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00
I V	0.00	0.00	0.00	0.00	0.00	0.00
S A	0.00	0.00	0.00	0.00	0.00	0.00
T L	0.00	0.00	0.00	0.00	0.00	0.00
O U	0.00	0.00	0.00	0.00	0.00	0.00
G E	0.00	0.00	0.00	0.00	0.00	0.00
R S	0.00	0.00	0.00	0.00	0.00	0.00
A	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.00	0.00	0.00	0.00	0.00

DISTRIBUTION FOR VERTICAL WATER LINE SAMPLING - TYPE = 2

PT. NO.	1	2
XM	0.00	105.00
YM	0.00	80.00
STW1	0.00	10.00
STW2	0.00	10.00

-----  
 SAMPLE VALUES FOR FACTOR OF SAFETY  
 -----

1.15764	1.15004	1.27369	1.14853	1.28817	1.11536	1.10971	1.37780	1.35458	1.29481
1.37648	1.48399	1.26568	1.22869	1.45833	1.27323	1.43553	1.22677	1.17704	1.38743
1.05386	1.26635	1.45103	1.08477	1.42999	1.32084	1.30842	1.17146	1.26150	1.32648
1.29341	1.11666	1.18710	1.39454	1.27616	1.27750	1.27513	1.20330	1.33288	1.16153
1.32505	1.23157	1.43262	1.44103	1.05782	1.17066	1.29003	1.23135	1.49329	1.49295
1.27541	1.42105	1.36727	1.55149	1.36460	1.26140	1.37470	1.16942	1.55376	1.48836
1.48686	1.34687	1.32588	1.30791	1.21543	1.36335	1.10786	1.32542	1.16728	1.21090
1.24067	1.25344	1.23433	1.42449	1.26026	1.26179	1.23416	1.13335	1.22210	1.08882
1.14346	1.11867	1.09410	1.37648	1.23133	1.22451	1.25982	1.39203	1.16266	1.09420
1.21409	1.24772	1.43039	1.09257	1.23525	1.24432	1.33101	1.12413	1.22969	1.34216
1.30456	1.37859	1.27461	1.35585	1.21877	1.40530	1.28536	1.16131	1.40700	1.23027
1.36846	1.11611	1.19656	1.18972	1.02180	1.13375	1.15397	1.27253	1.42068	1.19149
1.17506	1.38724	1.24511	1.15417	1.17389	1.16374	1.29028	1.21011	1.20423	1.19936
1.25703	1.06248	1.24309	.99986	1.23985	1.33964	1.13628	1.39372	1.11438	1.17595
1.13179	1.40006	1.13180	1.16131	1.25065	1.21031	1.16242	1.35901	1.21881	1.22744
1.16149	1.27923	1.22611	1.20066	1.24461	1.25411	1.20032	1.40327	1.43490	1.01799
1.42780	1.28814	1.31596	1.25946	1.15702	1.47107	1.34521	1.33463	1.38956	1.22356
1.37321	1.41705	1.43388	1.12653	1.35225	1.22614	1.26932	1.31912	1.18640	1.18862
1.22199	1.47427	1.25667	1.27488	1.29812					

MIN F.S.= .99986 MAX F.S.= 1.55376

-----  
 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS	INTERVAL	FREQUENCY											FRQ	PCT
		0	10	20	30	40	50	60	70	80				
1	1.00	1.03	.XXX										3	1.6
2	1.03	1.06	.X										1	.5
3	1.06	1.08	.XX										2	1.1
4	1.08	1.11	.XXXXXXX										7	3.8
5	1.11	1.14	.XXXXXXXXXXXX										12	6.5
6	1.14	1.17	.XXXXXXXXXXXXXXX										14	7.6
7	1.17	1.19	.XXXXXXXXXXXXXXX										13	7.0
8	1.19	1.22	.XXXXXXXXXXXXXXX										13	7.0
9	1.22	1.25	.XXXXXXXXXXXXXXXXXXXXXXX										24	13.0
10	1.25	1.28	.XXXXXXXXXXXXXXXXXXXXXXX										22	11.9
11	1.28	1.30	.XXXXXXXXXXXX										10	5.4
12	1.30	1.33	.XXXXXXXXXXXX										11	5.9
13	1.33	1.36	.XXXXXXXXXXXX										10	5.4
14	1.36	1.39	.XXXXXXXXXXXX										12	6.5
15	1.39	1.42	.XXXXXXXXXXXX										9	4.9
16	1.42	1.44	.XXXXXXXXXXXX										11	5.9
17	1.44	1.47	.XX										2	1.1
18	1.47	1.50	.XXXXXXX										7	3.8
19	1.50	1.53	.										0	0.0
20	1.53	1.55	.XX										2	1.1

-----  
 SAMPLE STATISTICS  
 -----

MEAN= 1.265 S.D.= .113 SKEWNESS= .041 KURTOSIS= 2.53 SAMPLE SIZE= 185

-----  
 PROBABILITY OF SLIDING  
 -----

P.F.= .97 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = 1.265 AND STD. DEV. = .113  
 P.F.= .59 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 1 + 0 + 14 WHERE

\*\*\* 1 CASES WERE NOT VALID CONFIGR.,  
 \*\*\* 0 CASES WERE NOT ACTIVE BLOCKS ,  
 \*\*\* 14 CASES WERE NOT PASSIVE BLOCKS.

## TWO-BLOCK SAMPLE CASE PROBABILISTIC ANALYSIS

SEE DESCRIPTION OF VARIABLES ON FIRST PAGE OF OUTPUT

\*\*\*\*\*  
INPUT DATA  
\*\*\*\*\*

ALPHA1	ALPHA2	ALPHA3	ALPHA4	H	X1	X4
60.0	30.0	143.0	60.0	100.0	115.0	-0.0
PHI1	PHI2	PHI3				
35.0	37.0	15.0				
COH1	COH2	COH3	DENR	DENH		
500.0	1000.0	200.0	160.0	62.4		
FA	THETAA	FP	THETAP	CONF	NH	
-0.0	-0.0	-0.0	-0.0	3.0	2.0	

POINTS ON PIEZOMETRIC LINE

PT. NO.	1	2
XW	0.00	105.00
YW	0.00	80.00

\*\*\*\*\*  
OUTPUT  
\*\*\*\*\*

X1	Y1	X2	Y2	X3	Y3	X4	Y4	X5	Y5	V0	VA
115.00	100.00	57.74	100.00	85.90	49.59	45.98	79.65	85.90	49.59	2280.44	2026.09
XL1	XL2	XL3	XL4	U1	U2	U3	U4	C1	C2	C3	
58.21	99.19	49.96	0.00	16164.3	49057.9	6479.2	0.0	29182.5	99185.8	9992.6	
R1	R2	R3	FXOHA	FYOHA	WA	FXQHP	FYOHP	WPL	WP	F2T	F2H
138654.9	-27127.8	166069.2	-3533.1	279702.3	324174.5	65454.2	-80891.8	-100035.0	364870.1	315312.9	380955.1
MPWA	MPWAL0	MPWAL	SF	FS							
1.13	1.23	-0.31	1.43	1.22							

\* - SENSITIVITY ANALYSIS WAS DONE ON THIS VARIABLE

\*\*\*\*\*  
PROBABILITY ANALYSIS - DETAIL OF INPUT  
\*\*\*\*\*

NO. OF SAMPLES	1ST RAND NO.	RAND SEED	PRINT CODE	GRAPH SIZE	STAT V9LS	NO. OF CLASSES
200.		123.	1.	80.	10.	20.000

RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = TRUNCATED GAUSSIAN, TYPE5 = EXPONENTIAL  
TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING DONE

VARIABLE	ALPHA1	ALPHA2	ALPHA3	ALPHA4	H	X1	X4
BASE	60.00	30.00	143.02	60.00	100.00	115.00	-0.00
TYPE	1	1	6	0	0	0	0
ST1	4.00	4.00	135.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	2.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	-0.00	0.00	0.00	0.00	0.00
H	-0.00	-0.00	.02	-0.00	-0.00	-0.00	-0.00
I V	-0.00	-0.00	.07	-0.00	-0.00	-0.00	-0.00
S A	-0.00	-0.00	.21	-0.00	-0.00	-0.00	-0.00
T L	-0.00	-0.00	.26	-0.00	-0.00	-0.00	-0.00
O U	-0.00	-0.00	.19	-0.00	-0.00	-0.00	-0.00
G E	-0.00	-0.00	.12	-0.00	-0.00	-0.00	-0.00
R S	-0.00	-0.00	.07	-0.00	-0.00	-0.00	-0.00
A	-0.00	-0.00	.05	-0.00	-0.00	-0.00	-0.00
M	-0.00	-0.00	.02	-0.00	-0.00	-0.00	-0.00

VARIABLE	PHI1	PHI2	PHI3	COH1	COH2	COH3
BASE	35.00	37.00	15.00	500.00	1000.00	200.00
TYPE	1	1	1	4	4	4
ST1	3.00	3.00	2.00	150.00	200.00	100.00
ST2	0.00	0.00	0.00	500.00	1000.00	200.00
ST3	0.00	0.00	0.00	900.00	1200.00	600.00

H	-0.00	-0.00	-0.00	0.00	0.00	0.00
I V	-0.00	-0.00	-0.00	0.00	0.00	0.00
S A	-0.00	-0.00	-0.00	0.00	0.00	0.00
T L	-0.00	-0.00	-0.00	0.00	0.00	0.00
O U	-0.00	-0.00	-0.00	0.00	0.00	0.00
G E	-0.00	-0.00	-0.00	0.00	0.00	0.00
R S	-0.00	-0.00	-0.00	0.00	0.00	0.00
A	-0.00	-0.00	-0.00	0.00	0.00	0.00
M	-0.00	-0.00	-0.00	0.00	0.00	0.00

VARIABLE	DENR	DENH	FA	THETAA	FP	THETAP
BASE	160.00	62.40	-0.00	-0.00	-0.00	-0.00
TYPE	1	0	0	0	0	0
ST1	5.00	0.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	0.00	0.00	0.00	0.00

H	0.00	0.00	0.00	0.00	0.00	0.00
I V	0.00	0.00	0.00	0.00	0.00	0.00
S A	0.00	0.00	0.00	0.00	0.00	0.00
T L	0.00	0.00	0.00	0.00	0.00	0.00
O U	0.00	0.00	0.00	0.00	0.00	0.00
G E	0.00	0.00	0.00	0.00	0.00	0.00
R S	0.00	0.00	0.00	0.00	0.00	0.00
A	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.00	0.00	0.00	0.00	0.00

DISTRIBUTION FOR VERTICAL WATER LINE SAMPLING - TYPE = 2

PT. NO.	1	2
XW	0.00	105.00
YW	0.00	80.00
STW1	0.00	10.00
STW2	0.00	10.00

-----  
 SAMPLE VALUES FOR FACTOR OF SAFETY  
 -----

1.19896	1.20540	1.32383	1.18827	1.33974	1.17395	1.16189	1.40367	1.41231	1.31088
1.40527	1.53394	1.30135	1.27839	1.50835	1.33566	1.44966	1.25584	1.19863	1.40124
1.12129	1.35772	1.47294	1.13439	1.49418	1.37600	1.34231	1.20780	1.32223	1.34770
1.32405	1.14625	1.20751	1.44822	1.28852	1.29786	1.28544	1.25778	1.35360	1.20049
1.36600	1.24957	1.47877	1.49124	1.38741	1.19373	1.30813	1.25850	1.50852	1.56155
1.31122	1.53442	1.39278	1.56347	1.39130	1.28840	1.38315	1.22618	1.64169	1.51003
1.53255	1.37786	1.37535	1.37066	1.28928	1.40123	1.13397	1.35540	1.22696	1.23537
1.27217	1.33650	1.27050	1.44076	1.31132	1.30363	1.28606	1.15860	1.25884	1.12023
1.18913	1.17871	1.16034	1.42164	1.26340	1.27175	1.30075	1.42742	1.20423	1.12262
1.25858	1.29193	1.48231	1.12123	1.26597	1.27421	1.38577	1.16171	1.26584	1.41816
1.35153	1.42595	1.33452	1.36337	1.23721	1.43047	1.33577	1.19185	1.46521	1.32421
1.42779	1.13869	1.25216	1.23536	1.07132	1.16190	1.22377	1.31082	1.47408	1.20975
1.23610	1.43394	1.27161	1.23450	1.18908	1.20883	1.33959	1.27638	1.27328	1.23489
1.32850	1.10841	1.24921	1.05188	1.28566	1.36429	1.18845	1.44399	1.13937	1.22541
1.16546	1.43974	1.17035	1.19183	1.28844	1.23298	1.20569	1.41599	1.24073	1.25242
1.19241	1.31499	1.28869	1.25523	1.31393	1.29242	1.24575	1.44596	1.47429	1.04858
1.48201	1.34657	1.37219	1.29199	1.18194	1.49286	1.38684	1.36357	1.42437	1.24305
1.41575	1.48339	1.46218	1.19377	1.40899	1.26018	1.29781	1.35037	1.24212	1.21679
1.27253	1.49838	1.30070	1.34386	1.36384					

MIN F.S.= 1.04858 MAX F.S.= 1.64169

-----  
 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS	INTERVAL	FREQUENCY											FRQ	PCT
		0	10	20	30	40	50	60	70	80				
1	1.05	1.08	.XXX										3	1.6
2	1.08	1.11	.X										1	.5
3	1.11	1.14	.XXXXXXX										7	3.8
4	1.14	1.17	.XXXXXXXXX										9	4.9
5	1.17	1.20	.XXXXXXXXXXXXX										13	7.0
6	1.20	1.23	.XXXXXXXXXXXXXXX										14	7.6
7	1.23	1.26	.XXXXXXXXXXXXXXXXX										18	9.7
8	1.26	1.29	.XXXXXXXXXXXXXXXXXXX										19	10.3
9	1.29	1.32	.XXXXXXXXXXXXXXXXXXXXX										22	11.9
10	1.32	1.35	.XXXXXXXXXXXXXXXXXX										13	7.0
11	1.35	1.37	.XXXXXXXXXXXXXXXXX										14	7.6
12	1.37	1.40	.XXXXXXXXXXXXX										11	5.9
13	1.40	1.43	.XXXXXXXXXXXXXXX										13	7.0
14	1.43	1.46	.XXXXXXX										7	3.8
15	1.46	1.49	.XXXXXXXXXXX										10	5.4
16	1.49	1.52	.XXXXX										5	2.7
17	1.52	1.55	.XXX										3	1.6
18	1.55	1.58	.XX										2	1.1
19	1.58	1.61	.										0	0.0
20	1.61	1.64	.X										1	.5

-----  
 SAMPLE STATISTICS  
 -----

MEAN= 1.307 S.D.= .115 SKEWNESS= .054 KURTOSIS= 2.59 SAMPLE SIZE= 185

-----  
 PROBABILITY OF SLIDING  
 -----

P.F.= .36 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = 1.307 AND STO. DEV. = .115  
 P.F.= 0.00 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 1 + 0 + 14 WHERE

\*\*\* 1 CASES WERE NOT VALID CONFIG.,  
 \*\*\* 0 CASES WERE NOT ACTIVE BLOCKS,  
 \*\*\* 14 CASES WERE NOT PASSIVE BLOCKS.

## TWO-BLOCK SAMPLE CASE PROBABILISTIC ANALYSIS

SEE DESCRIPTION OF VARIABLES ON FIRST PAGE OF OUTPUT

\*\*\*\*\*  
INPUT DATA  
\*\*\*\*\*

ALPHA1 60.0	ALPHA2 30.0	ALPHA3 143.0	ALPHA4 60.0	H 100.0	X1 115.0	X4 -0.0
PHI1 35.0	PHI2 37.0	PHI3* 20.0				
COH1 500.0	COH2 1000.0	COH3 200.0	DENR 160.0	OENW 62.4		
FA -0.0	THETAA -0.0	FP -0.0	THETAP -0.0	OENF 3.0	NW 2.0	

POINTS ON PIEZOMETRIC LINE

PT. NO.	1	2
XW	0.00	105.00
YW	0.00	80.00

\*\*\*\*\*  
OUTPUT  
\*\*\*\*\*

X1 115.00	Y1 100.00	X2 57.74	Y2 100.00	X3 85.90	Y3 49.59	X4 45.98	Y4 79.65	X5 85.90	Y5 49.59	VP 2280.44	VA 2026.09
XL1 58.21	XL2 99.19	XL3 49.96	XL4 0.00	U1 16164.3	U2 49057.9	U3 6479.2	U4 0.6	C1 29102.5	C2 99185.8	C3 9992.6	
R1 117054.3	R2 -102173.2	R3 181525.3	FXONA -3533.1	FYONA 279707.3	WA 324174.5	FXONP 65454.2	FYONP -80891.8	HPL -194134.9	HP 364870.1	F2T 317199.0	F2N 402513.4
WPA 1.13	WPA10 .90	WPA1 -.60	SF 1.72	FS 1.27							

\* - SENSITIVITY ANALYSIS WAS DONE ON THIS VARIABLE

\*\*\*\*\*  
PROBABILITY ANALYSIS - DETAIL OF INPUT  
\*\*\*\*\*

NO. OF SAMPLES	1ST RAND NO.	PRINT CODE	GRAPH SIZE	STAT VARS	NO. OF CLASSES
200.	123.	1.	80.	10.	20.000

RANGE AND TYPE OF DISTRIBUTION USED  
 TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = TRUNCATED GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING DONE

VARIABLE	ALPHA1	ALPHA2	ALPHA3	ALPHA4	H	X1	X4
BASE	60.00	30.00	143.02	60.00	100.00	115.00	-0.00
TYPE	1	1	6	0	0	0	0
ST1	4.00	4.00	135.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	2.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	-0.00	0.00	0.00	0.00	0.00

H	-0.00	-0.00	.02	-0.00	-0.00	-0.00	-0.00
I V	-0.00	-0.00	.07	-0.00	-0.00	-0.00	-0.00
S A	-0.00	-0.00	.21	-0.00	-0.00	-0.00	-0.00
T L	-0.00	-0.00	.26	-0.00	-0.00	-0.00	-0.00
O U	-0.00	-0.00	.19	-0.00	-0.00	-0.00	-0.00
G E	-0.00	-0.00	.12	-0.00	-0.00	-0.00	-0.00
R S	-0.00	-0.00	.07	-0.00	-0.00	-0.00	-0.00
A	-0.00	-0.00	.05	-0.00	-0.00	-0.00	-0.00
M	-0.00	-0.00	.02	-0.00	-0.00	-0.00	-0.00

VARIABLE	PHI1	PHI2	PHI3	COH1	COH2	COH3
BASE	35.00	37.00	20.00	500.00	1000.00	200.00
TYPE	1	1	1	4	4	4
ST1	3.00	3.00	2.00	150.00	200.00	100.00
ST2	0.00	0.00	0.00	500.00	1000.00	200.00
ST3	0.00	0.00	0.00	900.00	1200.00	600.00

H	-0.00	-0.00	-0.00	0.00	0.00	0.00
I V	-0.00	-0.00	-0.00	0.00	0.00	0.00
S A	-0.00	-0.00	-0.00	0.00	0.00	0.00
T L	-0.00	-0.00	-0.00	0.00	0.00	0.00
O U	-0.00	-0.00	-0.00	0.00	0.00	0.00
G E	-0.00	-0.00	-0.00	0.00	0.00	0.00
R S	-0.00	-0.00	-0.00	0.00	0.00	0.00
A	-0.00	-0.00	-0.00	0.00	0.00	0.00
M	-0.00	-0.00	-0.00	0.00	0.00	0.00

VARIABLE	DENR	OENW	FA	THETAA	FP	THETAP
BASE	160.00	62.40	-0.00	-0.00	-0.00	-0.00
TYPE	1	0	0	0	0	0
ST1	5.00	0.00	0.00	0.00	0.00	0.00
ST2	0.00	0.00	0.00	0.00	0.00	0.00
ST3	0.00	0.00	0.00	0.00	0.00	0.00

H	0.00	0.00	0.00	0.00	0.00	0.00
I V	0.00	0.00	0.00	0.00	0.00	0.00
S A	0.00	0.00	0.00	0.00	0.00	0.00
T L	0.00	0.00	0.00	0.00	0.00	0.00
O U	0.00	0.00	0.00	0.00	0.00	0.00
G E	0.00	0.00	0.00	0.00	0.00	0.00
R S	0.00	0.00	0.00	0.00	0.00	0.00
A	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.00	0.00	0.00	0.00	0.00

DISTRIBUTION FOR VERTICAL WATER LINE SAMPLING - TYPE = 2

PT. NO.	1	2
XW	0.00	105.00
YW	0.00	80.00
STW1	0.00	10.00
STW2	0.00	10.00



-----  
 SAMPLE VALUES FOR FACTOR OF SAFETY  
 -----

1.24825	1.26872	1.38178	1.23276	1.40070	1.24089	1.22151	1.43534	1.47782	1.32995
1.43950	1.59498	1.34411	1.33775	1.56455	1.41289	1.46651	1.28976	1.22317	1.41750
1.20341	1.46702	1.49844	1.19352	1.57002	1.44134	1.38118	1.24988	1.39499	1.37256
1.35906	1.17983	1.23261	1.51133	1.30332	1.32226	1.29706	1.32283	1.37735	1.24565
1.41495	1.27051	1.53117	1.58516	1.12127	1.22023	1.32963	1.29064	1.52810	1.64023
1.35600	1.67452	1.42108	1.57758	1.42215	1.31975	1.39291	1.29239	1.75406	1.53630
1.58711	1.41216	1.43341	1.44366	1.37683	1.44425	1.16482	1.38904	1.29995	1.26425
1.30903	1.43347	1.31169	1.45988	1.37116	1.35237	1.34617	1.18714	1.30067	1.15574
1.24300	1.24688	1.23873	1.47265	1.29986	1.32532	1.34663	1.46690	1.25378	1.15515
1.30888	1.34616	1.54405	1.15639	1.30023	1.30911	1.45398	1.20526	1.30639	1.51131
1.40609	1.48090	1.40230	1.37242	1.25876	1.46101	1.39431	1.22786	1.53071	1.44076
1.49792	1.16455	1.31718	1.28906	1.12870	1.19370	1.30702	1.35658	1.53883	1.23042
1.31189	1.48855	1.30169	1.33418	1.20625	1.26191	1.40061	1.35433	1.35667	1.27540
1.41705	1.16235	1.25631	1.11485	1.33908	1.39271	1.25128	1.50399	1.16722	1.28373
1.20368	1.48517	1.21572	1.22682	1.33178	1.25977	1.25532	1.48065	1.26582	1.28040
1.22856	1.35521	1.36358	1.31915	1.39592	1.33781	1.29859	1.49577	1.51809	1.08366
1.54544	1.41276	1.43847	1.33068	1.21057	1.51768	1.43689	1.39847	1.46707	1.26506
1.46633	1.56097	1.49532	1.27198	1.47478	1.29878	1.32964	1.38846	1.30811	1.25002
1.33276	1.52654	1.35342	1.42578	1.44196					

MIN F.S.= 1.08366 MAX F.S.= 1.75406

-----  
 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS INTERVAL	FREQUENCY										FRQ	PCT
	0	10	20	30	40	50	60	70	80			
1 1.08	1.12	.XX									2	1.1
2 1.12	1.15	.XX									2	1.1
3 1.15	1.18	.XXXXXXXX									8	4.3
4 1.18	1.22	.XXXXXXXX									9	4.9
5 1.22	1.25	.XXXXXXXXXXXXXXXXXX									17	9.2
6 1.25	1.28	.XXXXXXXXXXXXXXXXXX									16	8.6
7 1.28	1.32	.XXXXXXXXXXXXXXXXXXXX									22	11.9
8 1.32	1.35	.XXXXXXXXXXXXXXXXXXXX									19	10.3
9 1.35	1.39	.XXXXXXXXXXXXXXXXXXXX									16	8.6
10 1.39	1.42	.XXXXXXXXXXXXXXXXXXXX									18	9.7
11 1.42	1.45	.XXXXXXXXXXXXXXXXXXXX									14	7.6
12 1.45	1.49	.XXXXXXXXXXXXXXXXXXXX									14	7.6
13 1.49	1.52	.XXXXXXXXXXXX									10	5.4
14 1.52	1.55	.XXXXXXXXXX									8	4.3
15 1.55	1.59	.XXXXXX									5	2.7
16 1.59	1.62	.XX									2	1.1
17 1.62	1.65	.X									1	.5
18 1.65	1.69	.X									1	.5
19 1.69	1.72	.									0	0.0
20 1.72	1.75	.X									1	.5

-----  
 SAMPLE STATISTICS  
 -----

MEAN= 1.357 S.D.= .121 SKEWNESS= .100 KURTOSIS= 2.85 SAMPLE SIZE= 185

-----  
 PROBABILITY OF SLIDING  
 -----

P.F.= .16 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = 1.357 AND STD. DEV. = .121  
 P.F.= 0.00 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 1 + 0 + 14 WHERE

\*\*\* 1 CASES WERE NOT VALID CONFIGR.,  
 \*\*\* 0 CASES WERE NOT ACTIVE BLOCKS ,  
 \*\*\* 14 CASES WERE NOT PASSIVE BLOCKS.

# SENSITIVITY OF FACTOR OF SAFETY TO PHI3

FACTOR OF SAFETY	PHI3	0.0	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
1.19	10.00	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I
		.	.	.	*	.	.	.	.	.
1.22	15.00	.	.	.	*	.	.	.	.	.
		.	.	.	.	.	.	.	.	.
1.27	20.00	.	.	.	*	.	.	.	.	.
		I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I	I.....I
		0.0	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
		FACTOR OF SAFETY								

## ...PROBABILITY OF SLIDING AS A FUNCTION OF PARAMETER PHI3

	PHI3	PF (%)	0	10	20	30	40	50	60	70	80	90	100
1	10.00	.59	*	.	.	.	.	.	.	.	.	.	.
2	15.00	0.00	*	.	.	.	.	.	.	.	.	.	.
3	20.00	0.00	*	.	.	.	.	.	.	.	.	.	.

## REFERENCES

B-1. Kuykendall, L. and Goodman, R.E. Unpublished report, CANMET, Department of Energy, Mines and Resources, Ottawa, Canada; 1975.

B-2. Sultan, H.A. and Seed, H.B. "Stability of sloping core earth dams"; Journal of Soil Mechanics and Foundation Division, A.S.C.E.; v. 93, no. SM4, pp 45-67; 1967.



## APPENDIX C

### PROGRAM DOCUMENTATION OF WINTAM

(wedge along line of intersection analysis including Monte Carlo simulation)



## ABSTRACT

The program determines a factor of safety against sliding of a rigid body down the line of intersection formed by two planar discontinuities. A general wedge problem can be solved. The factor of safety is defined as the ratio of resisting forces to driving forces. Any input parameter may be varied automatically to determine the sensitivity of the factor to changes in that parameter. The probability of instability can be determined by means of a Monte Carlo overlay technique.

## PROGRAM IDENTIFICATION

Program Title: Three-Dimensional Sliding Wedge Analysis

Code Name: WINTAM (WEDGE ALONG LINE OF INTERSECTION ANALYSIS INCLUDING MONTE CARLO SIMULATION)

Writer: G. Major, F. Marder, H-S. Kim

Organization: Dames & Moore

Date: June, 1974

Updates: November, 1974; August, 1975

Source language: Fortran IV

Availability: Mining Research Laboratories, CANMET, Department of Energy, Mines and Resources, 555 Booth Street, Ottawa, Canada, K1A 0G1

## ENGINEERING DOCUMENTATION

1. This program performs a limit equilibrium analysis of the stability of a slope containing a tetrahedral wedge formed by the intersection of two discontinuity planes. Any influence of moments is neglected. It allows for the inclusion of different shear strengths on each of the potential sliding surfaces, the introduction of a tension crack, any inclination of the upper wedge surface, a range of groundwater pressures and the influence of an external force. External forces may be due to loading, reinforcement or a pseudostatic representation of earthquake loading.

2. The program includes a kinematic check which tests whether the line of intersection of the wedge can exit in the slope face. This facility is needed in probability analyses where the distribution of joint orientations may result in some chance of lines of intersection not exiting in the face.

3. Simpler methods provide satisfactory means of analyzing wedges when the shear strength can be considered purely frictional and there are no external forces. Consequently, it is suggested that this program be used only for the detailed investigation of wedges which have been shown to be potential sliding cases. The sensitivity analysis and probability capabilities are particularly useful at this level as aids in deciding

on stabilization procedures.

4. The analysis is based on a scalar analytical solution for the case shown in Fig C-1 (C-1).

5. The program recognizes five separate instances of wedge instability which are designated: Case 1 No tension crack or water present (Fig C-2(a) and C-3(a))

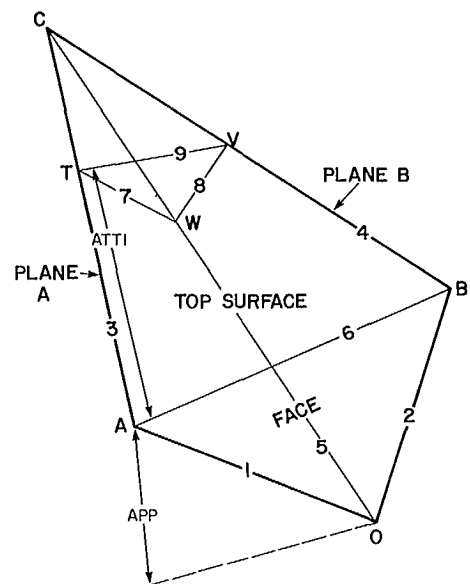


Fig C-1 - Numbering of wedge planes and lines of intersection as used in wedge analysis.



X LOCATION FROM WHICH PERSPECTIVE REPRESENTATIONS (FIGURE 3) ARE VIEWED

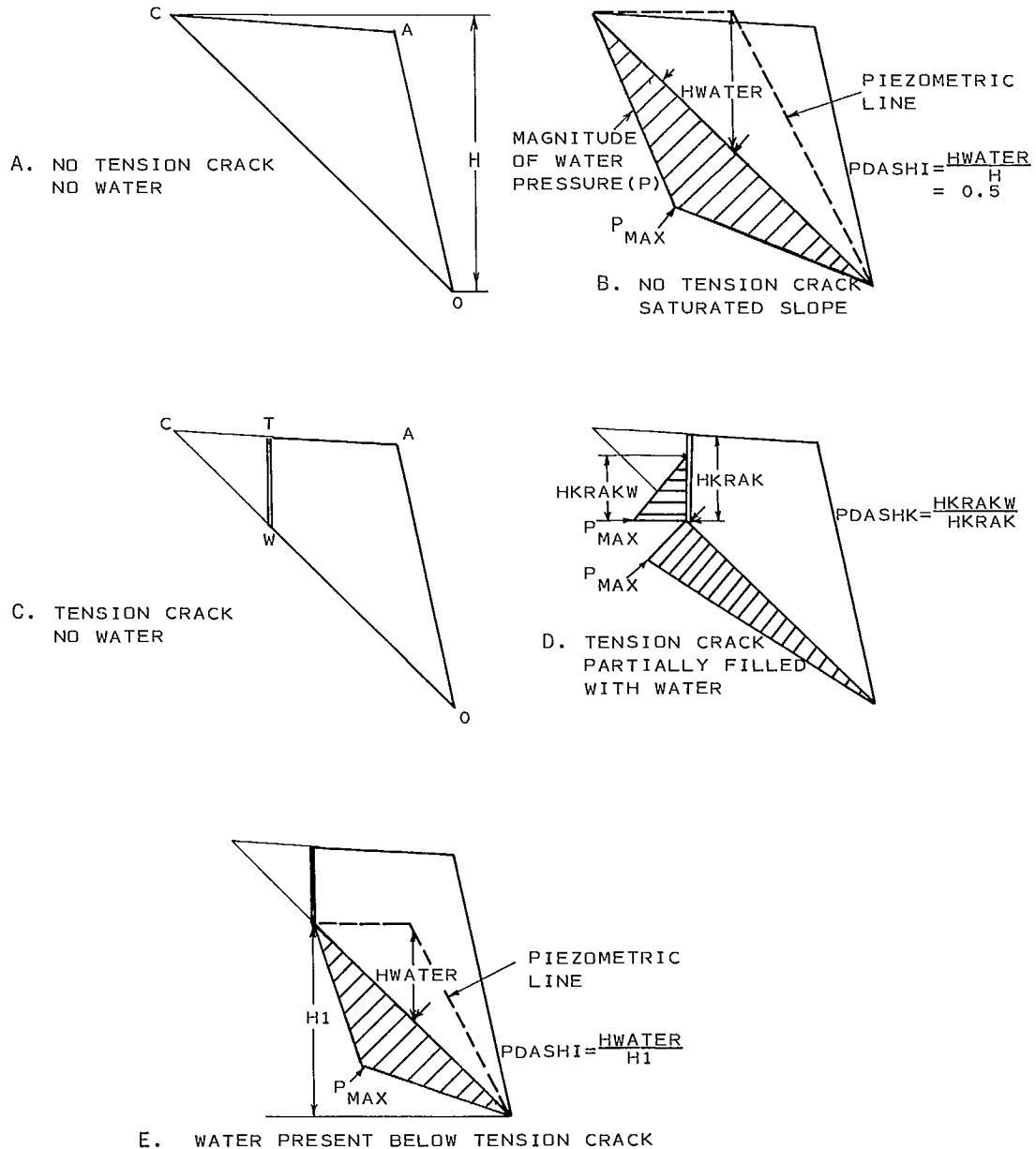


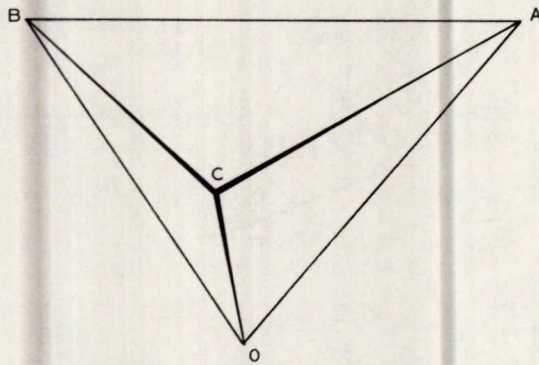
Fig C-2 - Assumed water pressures along the line of intersection and tension crack for the five basic cases considered by the program.

- Case 2 No tension crack, but water is present and is modelled by a bi-linear piezometric line (Fig C-2(b) and C-3(b))
- Case 3 A tension crack is present but there is no water (Fig C-2(c) and C-3(c))
- Case 4 A tension crack is present with water within the tension crack (Fig C-2(d) and

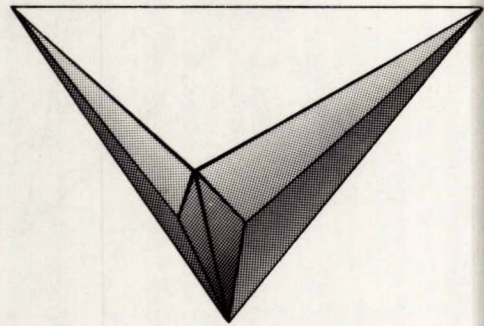
C-3(d))

- Case 5 A tension crack is present with the water table passing below the bottom of the tension crack (Fig C-2(e) and C-3(e)).

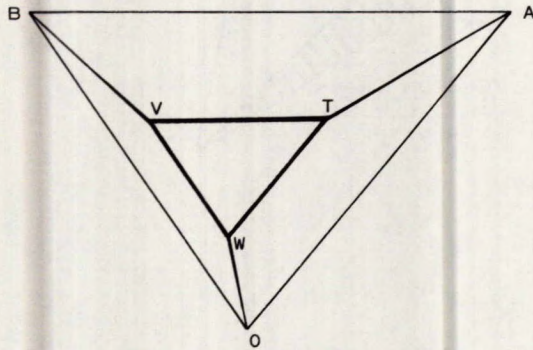
6. The Monte Carlo overlay routines, which form the basis of the probability analyses and have a very general application in slope stability



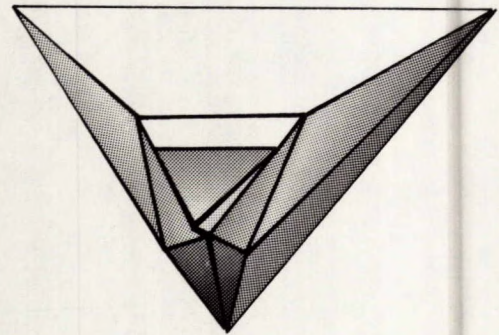
A. NO TENSION CRACK  
NO WATER



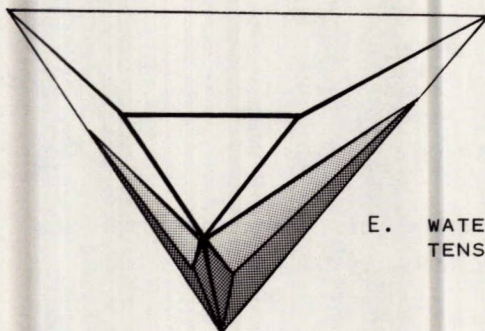
B. NO TENSION CRACK  
SATURATED SLOPE



C. TENSION CRACK  
NO WATER



D. TENSION CRACK PARTIALLY  
FILLED WITH WATER



E. WATER PRESENT BELOW  
TENSION CRACK

WATER PRESSURE  
DISTRIBUTIONS  
SHOWN SHADED

Fig C-3 - Perspective representations of water pressure distributions assumed in fig C-2, viewed from behind the wedge (position x in fig C-2a).

and other fields, have been documented in detail separately.

#### Method of Solution

7. From the basic input data, most of which will be forthcoming from routine investigations, the program initially calculates the geometry of the wedge. The areas of the potential sliding planes and the tension crack are calculated. The coefficients for determining the normal reactions due to externally applied forces and the coefficient for determining the component of this force acting down the line of intersection are determined. The forces due to water pressure are then calculated, and appropriate information is substituted into a general factor of safety equation. The total force available to resist sliding is calculated; this comprises the cohesive strength on each plane multiplied by the area of that plane plus the total effective normal reaction on each plane multiplied by the coefficient

of friction of that plane. The total resisting force is divided by the force tending to induce sliding. These are the sum of the components of the weight, externally applied forces and the force of the water in the tension crack acting down the line of intersection of the two planes. The program will then repeat any steps necessary to calculate a new factor of safety caused by the variation of any input parameter during the sensitivity analysis.

8. The dip directions of the lines of intersection are calculated from the formula:

$$\alpha_i = \arctan \left( \frac{\tan \psi_a \cdot \cos \alpha_a - \tan \psi_b \cdot \cos \alpha_b}{\tan \psi_b \cdot \sin \alpha_b - \tan \psi_a \cdot \sin \alpha_a} \right)$$

and the dips of the lines of intersection from the formula:

$$\psi_i = \arctan \left( \tan \psi_b \cos (\alpha_b - \alpha_i) \right)$$

The meaning of the terms is shown in Fig C-4.

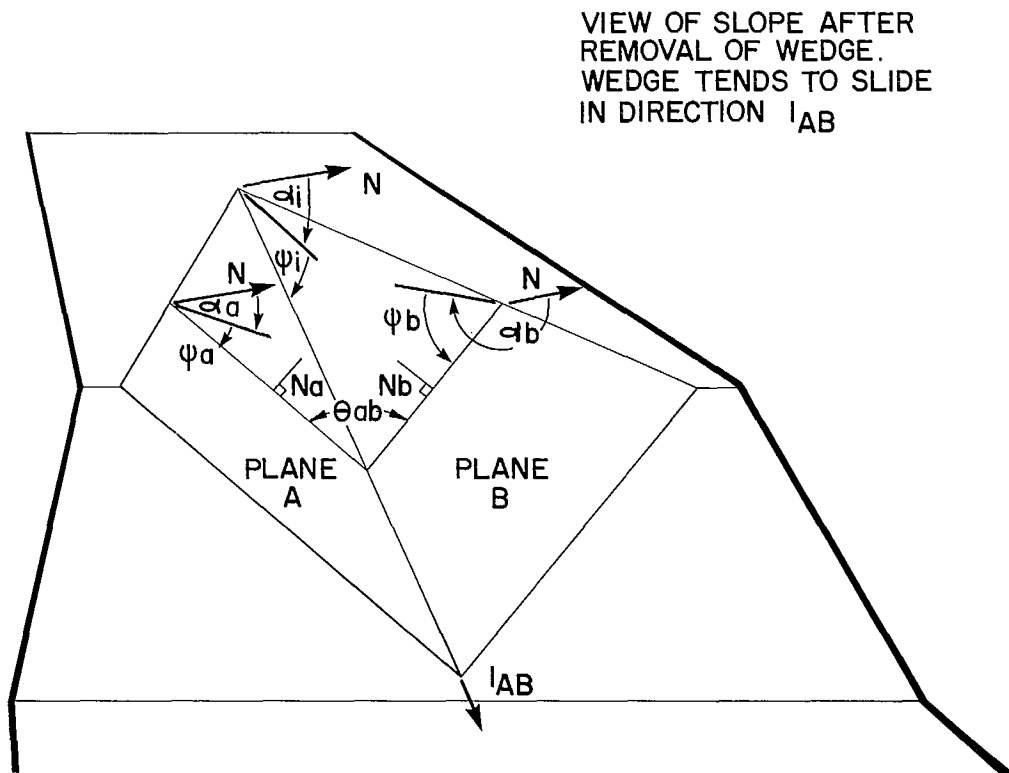


Fig C-4 - Definition of terms in the calculation of dips and dip direction of lines of intersection of planes.

9. The angles between the lines of intersection are calculated using:

$$\theta_{ab} = \arccos \left( \cos \psi_a \cdot \cos (\alpha_a - \alpha_b) + \sin \psi_a \cdot \sin \psi_b \right)$$

10. Length AC (Fig C-1) is determined by the application of the sine rule to give:

$$AC = AO \frac{\sin \theta_{15}}{\sin \theta_{35}}$$

which then gives TC as AC-AT.

11. The areas of planes A and B are calculated as half the product of two sides and the sine of the included angle. The application of the sine rule reduces the equations to be in terms of the length AC.

12. The areas of sliding surfaces are determined by subtracting the triangular areas behind the tension crack, and these are calculated in terms of TC.

13. Similarly, the area of the triangular tension crack is calculated in terms of the length TC.

14. The coefficients for the determination of effective normal reactions are obtained by resolving the forces in the directions of these reactions using the equation:

$$m_{a \cdot b} = \cos \psi_a \cdot \cos \psi_b (\alpha_a - \alpha_b) + \sin \psi_a \cdot \sin \psi_b$$

where  $m_{a \cdot b} = \cos \theta_{ab}$  ie, the angle between the orientations  $(\alpha_a, \psi_a)$  and  $(\alpha_b, \psi_b)$ .

15. The coefficients for the effective normal reactions are then of the form:

$$\frac{(m_{na \cdot nb} \cdot m_{F \cdot nb} - m_{F \cdot na})}{(1 - m_{na \cdot nb}^2)}$$

or

$$\frac{(m_{na \cdot nb} \cdot m_{F \cdot na} - m_{f \cdot nb})}{(1 - m_{na \cdot nb}^2)}$$

where F is the force for which the coefficient is being derived, and  $n_a, n_b$  are directions normal to plane A and plane B, respectively. Negative coefficients occur if the input information defines a case of single plane sliding, which occurs when

one of the assumed shear surfaces becomes a release plane. In such cases, the coefficient is set to zero to avoid the meaningless situation of negative shear strengths and an explanation is printed out.

16. The kinematic possibility of wedge sliding is checked by determining whether the line of intersection of the wedge emerges in the slope face. This is done by comparing the true dip of the line of intersection with the apparent dip of the slope face in the dip direction of the line of intersection,  $(\gamma_{\text{apparent}})$ . The apparent dip is determined using the formula:

$$\psi_{\text{apparent}} = \arctan [\tan \psi_F \cos(\alpha_I - \alpha_F)]$$

If the dip of the line of intersection is greater than  $\psi_{\text{apparent}}$ , sliding is kinematically impossible.

17. The weight of the wedge is calculated from the formula:

$$W = 1/6 \gamma K \left\{ AC^3 \frac{\sin^2 \theta_{13} \sin \theta_{25}}{\sin^2 \theta_{15} \sin \theta_{24}} - TC^3 \frac{\sin^2 \theta_{37} \sin \theta_{59}}{\sin^2 \theta_{57} \sin \theta_{48}} \right\}$$

where

$$K = (1 - \cos^2 \theta_{34} - \cos^2 \theta_{35} - \cos^2 \theta_{45} + 2 \cos \theta_{34} \cos \theta_{35} \cos \theta_{45})^{\frac{1}{2}}, \gamma = \text{density of the rock.}$$

18. For the case of a wedge with no tension crack, the maximum water pressure is determined as shown in Fig C-2(b):

$$P_{\text{max}} = \gamma_w \text{ HWATER}$$

19. A saturated slope is modelled by specifying the maximum head of water as one half the total height of the wedge, PDASHI = 0.5. The forces due to water pressure are calculated assuming a tetrahedral distribution of pressure over the entire shear surfaces. This is equivalent to assuming that maximum pressure occurs at the mid point of the line of intersection and decreases linearly to zero at each free surface, as shown in perspective in Fig C-3(b). This gives the total force due to water pressure on each

shear surface as

$$U = \frac{1}{3} P_{\max} A$$

where A is the total area of the shear surface.

20. When the maximum head of water is specified as less than one half of the slope height ie,  $0. < PDASHI < 0.5$ , the calculation is similar but the area over which the water is assumed to act is

reduced. The top line along which the pressure becomes zero is parallel to the top of the wedge, but lies above the toe by an amount which is proportional to PDASHI. This pressure distribution is for a piezometric line which is horizontal for half the distance over which it acts on the wedge and then decreases linearly to the toe of the slope as shown in Fig C-5(a). The horizontal segment is at a height of  $PDASHI * 2 * H$  above the toe of

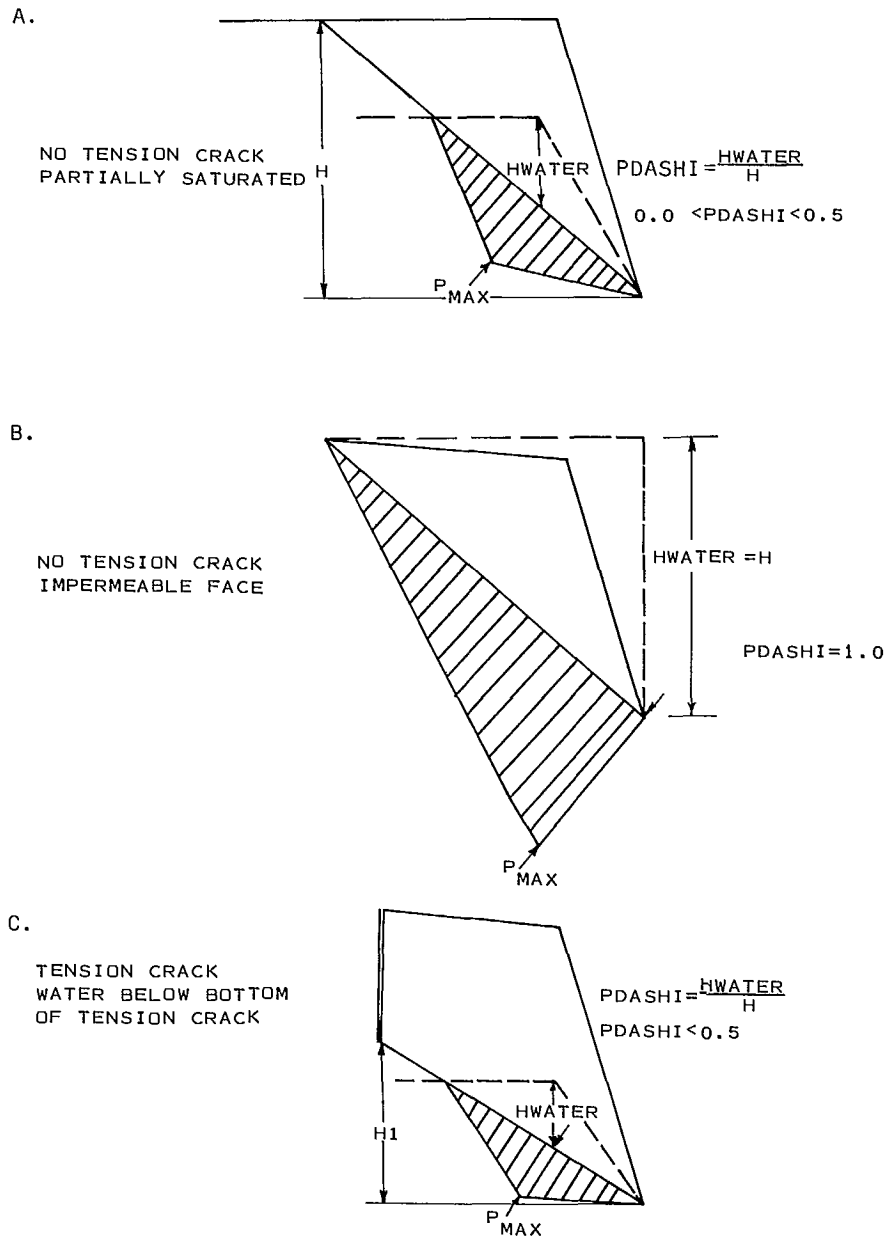


Fig C-5 - Other water pressure distributions allowed for in the program.

the wedge.

21. When the maximum head of water is specified as being equal to the full height of the wedge, ie, PDASHI = 1.0, this is equivalent to assuming that the maximum pressure occurs at the toe of the slope and falls off linearly to zero at the intersection of the shear surface with the top of the wedge. This is equivalent to a piezometric line which is horizontal for the full length of the line of intersection of the wedge. Thus the pressure increases hydrostatically along both the line of intersection of the wedge and along the intersection of the shear surface with the slope face Fig C-5(b). Again, the total force is found by determining the volume of the tetrahedron, which is:

$$U = \frac{1}{3} P_{\max} A$$

This is an extreme distribution of pressure and is likely to arise only in the case of a completely impermeable face, as may occur if the face freezes. For the range  $0.5 \leq \text{PDASHI} \leq 1.0$ , the water pressure is assumed to act over the entire shear surface. The total water force is therefore linearly dependent on the value of PDASHI used.

22. In the case of a water filled tension crack, which is specified by PDASHK = 1.0, the maximum water pressure, P, is calculated as:

$$P = \gamma_w \frac{TC}{2} \frac{\sin \theta_{35}}{\sin \theta_{57}} \left[ \sin \psi_7 + \frac{\sin \theta_{79}}{\sin \theta_{89}} \sin \psi_8 \right]$$

P is reduced according to the depth of water in the tension crack, as shown in Fig C-2(d). The horizontal force, V, due to this water pressure is:

$$V = \frac{1}{3} P_{\max} A_C$$

where  $A_C$  is the area of the tension crack over which the water pressure acts. The uplift force on the sliding planes, U, is determined by

$$U = \frac{1}{3} P_{\max} A_f$$

where  $A_f$  is the area of the shear surface in front of the tension crack. This pressure distribution is shown in perspective in Fig C-3(d). Using this shear surface area will be conservative if the level of water in the tension crack is below the top surface of the wedge.

23. When water is present below the base of the tension crack ie,  $0.0 \leq \text{PDASHI} \leq 0.5$ , the maximum water pressure,  $P_{\max}$ , is determined as:

$$P_{\max} = \frac{1}{2} \gamma_w H_1$$

for the case of a phreatic surface coincident with the base of the tension crack, where  $H_1$  is the vertical distance from the toe of the slope to the base of the tension crack as shown in Fig C-2(e).  $P_{\max}$  is varied according to the value of PDASHI. The uplift force is then calculated as:

$$U = \frac{1}{3} P_{\max} A_b$$

where  $A_b$  is the area of the shear surface below the base of the tension crack for the case of the water table coincident with the base of the tension crack ie, PDASHI = 0.5, as shown in perspective in Fig C-3(e). This area is reduced for less severe water pressure distributions in the manner described for the case of a slope with no tension crack, but with the height of the horizontal segment of the piezometric line being related to  $H_1$  instead of to H as shown in Fig C-5.

24. It should be noted that approaching the dry tension crack case by having PDASHK approach 0.0 does not converge on the same result as by approaching a piezometric line passing through the bottom of the tension crack by having PDASHI approach 0.5, since the maximum water pressures and the affected areas differ.

25. If the height of the wedge is varied during a sensitivity analysis, the water pressure distribution maintains the same form, so that the water forces are varied with the height of the slope.

26. The factor of safety is calculated from the equation:



$$F = \{C_A A_A + C_B A_B + (q.W + r.V + s.T - U_A) \tan \phi_A + (x.W + y.V + z.T - U_B) \tan \phi_B\} / (m_{W.5} W + m_{V.5} V + m_{T.5} T)$$

27. In a sensitivity analysis, the factors of safety and the values of any varied parameters are stored in arrays before the program returns for any modification specified for the input values.

28. The factors of safety corresponding to the specified input values can be plotted and printed if required. The results of the intermediate steps in the calculations can also be printed if specified.

29. In the case of a probabilistic analysis, all variables are assumed independent. Stochastic variables may be specified using any of the following six distributions:

- gaussian or normal distribution,
- triangular distribution, which can be skewed,
- uniform or flat distribution,
- truncated normal distribution with specified left and right side cutoffs,
- exponential distribution and
- histogram input by the user.

30. The type of distribution is defined on input. Any distribution can be used for any input parameter except that the location of the tension crack must be considered deterministic. Additional distributions can be added by a simple modification of the program, as outlined in the documentation of the Monte Carlo overlay.

31. The location of the tension crack is specified on input as ATTI, the distance from the slope crest to the tension crack along the trace of plane A (Fig C-1). It is redefined within the program in terms of the ratio of the length CT to CA, which is kept constant during changes in the dimensions of the wedge. The calculated distance from the crest to the tension crack along plane A is printed out as "wedge depth", the printed value of ATTI being constant, except when the parameter is varied in a sensitivity analysis. This scaling is more realistic than maintaining the tension

crack at a fixed distance from the slope crest. It is also necessary to ensure that whatever wedge geometry is defined by a sensitivity or probabilistic analysis, the tension crack will always cross the line AC. Since the ratio is calculated from the first set of input data, the basic input data must define a wedge for which sliding is kinematically possible, and the length specified for ATTI must be less than the length AC.

32. The sampling technique used results in a cutoff of the sampled normal distributions at six standard deviations on either side of the mean. As less than 0.01% of the area under a normal curve lies outside this range, this limitation is not significant.

33. Stochastic variables for which values outside a given range are unacceptable, eg, negative cohesions, friction angles or water parameters, can be modelled using the triangular, uniform, truncated normal, exponential or histogram distributions. Cutoffs must be specified for both left and right sides of a truncated normal distribution, so if there is no physical reason for a limit on one side, setting this at least six standard deviations from the mean will ensure there is no effective termination to the sampling range.

34. For a probabilistic analysis, the factor of safety is stored and the calculations are repeated a specified number of times, using new sets of input values selected by the Monte Carlo overlay. The distribution of the factors of safety so calculated is plotted, and the mean, standard deviation, skewness and kurtosis of the values are printed out.

35. Skewness is defined as:

$$\frac{n(3^{\text{rd}} \text{ moment about the mean})^2}{(2^{\text{nd}} \text{ moment about the mean})^3}$$

where  $n = +1$  if the third moment is positive and  $n = -1$  if negative. Skewness of zero indicates a symmetrical normal distribution; positive skewness is to the right; negative skewness is to the left.

36. Kurtosis is defined as:

$$\frac{4^{\text{th}} \text{ moment about the mean}}{(2^{\text{nd}} \text{ moment about the mean})^2}$$

This is a measure of the peakedness of the distribution and equals 3.0 if the distribution is normal. Higher values indicate the distribution is more peaked.

37. In a probabilistic analysis, the probability of instability is determined as the probability of the factor of safety falling below the limiting equilibrium condition. The probability of sliding is estimated by the following three methods.

1. Calculating the mean and standard deviation of the calculated factors of safety. The normal distribution curve defined by these two statistical parameters is then assumed to be that of the population of factors of safety. The probability of instability is determined by the following integral:

$$\frac{1}{\sqrt{2\pi} \cdot S} \int_{-\infty}^X e^{-(t-m)^2/(2S^2)} dt$$

where  $X$  is the critical factor of safety corresponding to the limiting equilibrium condition,  $m$  the mean factor of safety and  $S$  the standard deviation of the factor of safety. This integral can be evaluated using Hasting's polynomial approximation. The use of a probability distribution curve serves to even out the irregularities to be expected from random sampling techniques, especially where small sample sizes are used (C-2).

2. Fitting a normal curve to the calculated factors of safety which minimizes the chi-square. The probability of instability is then determined by using this distribution in a manner similar to that described for the first estimate. If the distribution of factors of safety is normal, this technique will provide the best estimate of the distribution and will therefore result in the best estimate of the probability of instability.

3. Counting the number of calculated factors of safety which fall below the limiting equilibrium condition. The probability of instability is then given by expressing this number as a percentage of the total sample size. This method has the great advantage that no assumptions need be made concerning the distribution of factors of safety. For sample sizes below about 100, the sample scatter has an adverse effect on the consistency of estimates obtained from this method. For large samples of about 1000, this method provides a very reliable estimate.

38. Marked differences in these three estimates may indicate either that the distribution is genuinely non-normal or that some input values are unacceptable, and these inconsistencies must be explained and understood before the determined probability of instability can be accepted.

39. When the Monte Carlo overlay is used for cases in which the factor of safety is a non-linear function of the input variables, the distribution of the calculated factors of safety may depart considerably from normality. Any departure from normality will be reflected in the value of skewness and kurtosis, and in the chi-square if this option is used. These values therefore determine whether the defined normal distributions provide a sufficiently accurate measure of the probability of instability or whether a direct count of the factors of safety falling below the limiting equilibrium condition must be used.

40. When wedges are sampled for which sliding is kinematically impossible, a factor of safety has no physical significance. Therefore, the distribution of factors of safety cannot be used in estimating the probability of instability. In this case the probability is determined from a direct count. The number of wedges for which sliding is kinematically impossible is printed out, and each of these is counted as a stable case in calculating the probability of instability.

41. The computer program for these analyses consists of a main program which controls the nine



subroutines that perform the input, analyses, and output for safety factor, sensitivity and probabilistic analyses. A list of these subroutines and their function appears below. The Monte Carlo overlay subroutines, which perform random sampling, statistical analysis and plotting, have been documented separately.

#### Program Capabilities

42. The program will solve the most general wedge problem, taking as its input data information on the geometry of the wedge in the form in which it is most readily measured in the field. Initially, a factor of safety is calculated. The input parameters may then be varied up to 40 times. The values are input eight per card on up to five cards. While any parameter is being varied, all other parameters are held at their original input values. Should the simultaneous variation of more than one parameter be required, a separate run is necessary.

43. The basic input information will usually consist of the values considered most appropriate for the case being investigated. A sensitivity analysis will quickly establish, for the limits of uncertainty associated with each parameter, to which parameters the factor of safety is most sensitive. Cohesion and water pressure will usually be found to have the largest influence on the factor of safety.

44. A probabilistic analysis can generate plots showing the probability of sliding for various slope heights and angles. These curves are, of course, influenced by the assumptions described above for the location of the tension crack and for the water pressures.

45. It is assumed that sliding will be down the line of intersection, with contact being maintained on both discontinuity planes. Thus the possibility of rotation is not considered.

46. The rock which constitutes the wedge is assumed to remain intact. Hence the effect of any discontinuities within the block in promoting the breaking up of the wedge is not considered. The program does not allow for other instability modes such as toppling, progressive development of

tension cracks, or any other time-dependent aspect of stability.

47. The shear strength of the sliding surfaces is assumed to be adequately represented by the relationship:

$$\tau = c + \sigma' \tan \phi$$

where  $\tau$  = shear strength,

$c$  = cohesion intercept on shear stress - normal stress plot,

$\sigma'$  = effective normal stress and

$\phi$  = friction angle of the surfaces.

All values may differ for each surface.

48. Any tension crack must be within the wedge and may not intersect the slope face.

49. There is no facility for an automatic determination of the critical tension crack position, but this position can be determined by varying the distance of the tension crack from the crest to find the location which results in the minimum factor of safety. This variation should normally be done for the condition of no water.

50. Specifying the water force in terms of the slope height has the effect of changing the phreatic surface according to the orientation of the line of intersection of the wedge. Physically, it would be more desirable to have the absolute location of the phreatic surface as an independent variable. The manner in which the water forces are specified does not allow this due to the three-dimensional nature of the problem. Care should be taken in both deterministic and probabilistic analyses to ensure that as the dip of the line of intersection approaches that of the slope face, the water conditions specified do not result in unrealistically high uplift forces.

51. The form of the factor of safety equation requires that any applied force be active rather than passive, eg, assume tensioned rockbolts or prestressed cables rather than anchor bars. Passive forces might be approximated by equivalent active forces.

#### Data Input

52. Data input is punched on cards and is described in detail in Exhibit C-1.

53. Card A contains a description of up to 80

alphanumeric characters which identify the problem.

54. Card B contains control information. A value must be assigned to CALCS, where the allowable values have the following meaning:

CALCS = 0. a probabilistic analysis is to be performed using the ratio of driving to resisting forces to calculate the factor of safety;

CALCS = -1. a probabilistic analysis is to be performed taking the difference of driving and resisting forces to determine the margin of safety;

CALCS = 1. a factor of safety analysis is required.

NOSENS is the number of variables for which a sensitivity analysis is desired eg, NOSENS = 0 means no sensitivity analysis is required. IPRINT controls program output.

55. The next series of cards (C, D and E in Exhibit C-1 contain geometry, material properties properties and other data which describe the basic case. The dips,  $\psi$ , and dip directions,  $\alpha$ , of the four planes which define the tetrahedral wedge, and those of the tension crack if appropriate, are input. Dip directions should lie between  $0^\circ$  and  $360^\circ$ , and dips should lie between  $0^\circ$  and  $90^\circ$ . Other information includes friction angles,  $\phi$ , and cohesion values,  $c$ , the height of the wedge corner A above the toe of the wedge, 0, the distance back from the crest to the tension crack along the trace of plane A, the densities of the rock and water, the magnitude of any externally applied force, and the dip and dip direction of any applied force.

56. ATTI corresponds to the distance AT, Fig C-1, and should be input as -1., if the case being considered does not include a tension crack.

57. PDASHI specifies the water condition for a wedge with no tension crack, and expresses the maximum head of water, HWATER, as a decimal fraction of the total wedge height, H, in Fig C-2(b); hence:

$$PDASHI = \frac{HWATER}{H}$$

PDASHI may take the numerical values of:

PDASHI = 0.0 for a dry slope

PDASHI = 0.5 for a fully saturated slope

0. < PDASHI < 0.5 for a partially saturated slope

PDASHI = 1.0 for a saturated slope with an impermeable face.

58. PDASHK specifies the water condition for a wedge with water in the tension crack and expresses the height of water in the tension crack as a decimal fraction of the total crack height, Fig C-2(d); hence:

$$PDASHK = \frac{HKRAKW}{HKRAK}$$

PDASHK may take the following values:

PDASHK = 0.0 for a dry slope

PDASHK = 1.0 for a water-filled tension crack

0. < PDASHK < 1.0 for a tension crack partially filled with water.

59. As the distance CT in Fig C-1 becomes small, the forces due to water pressure in the water-filled tension crack case, as determined by this model, may become unrealistically small. Although the user should be aware of the limitation, it is unlikely that a tension crack would form sufficiently far back from the crest to make this a problem.

60. The case of the water table situated below the bottom of the tension crack can be modelled by specifying a value for PDASHI. This results in a similar pressure distribution to the no-tension-crack case. The height over which the water pressure is assumed to act is determined by the height from the toe to the bottom of the tension crack, rather than over the full slope height. The top line of the area affected by the pressure is assumed horizontal, Fig C-2(e).

61. It should be noted that non-zero values of PDASHI and PDAHK cannot be input at the same time.

62. Any consistent system of units may be used for the input data, with the exception that angles must be input in degrees.

63. When a probabilistic analysis is undertaken, ie, CALCS = 0. or CALCS = -1., the user must also specify certain statistical parameters and options on the F card. The number of times the Monte Carlo overlay is to be used to sample the specified input distributions is defined by inputting a value for NSAMPL, which may be given any value up to 1000. As this corresponds to the number of sample points used in estimating the distribution of the factors of safety, the greater the value of NSAMPL the more reliable is the final determination of the probability of instability. A value for NSAMPL of 200 will usually give a suitable compromise between computing costs and the accuracy of the calculated probability.

64. A value of MFIRST can also be input to specify the starting value for the random number generator used in the Monte Carlo overlay. This can be specified as any odd number, and if not specified, MFIRST is automatically set at 1,111,111.

65. NSTV is the number of parameters which are to be considered as stochastic variables.

66. BINSIZ specifies the number of divisions into which the calculated factors of safety are divided for the ideogram plot. It can be specified as any value between 1. and 100., in which case it defines the number of classes; if it is less than 1., it defines the class interval used for the plot. To provide a reasonable shape for the plotted distribution of safety factors, the values of NSAMPL and BINSIZ should be related approximately as follows:

NSAMPL = 100.            BINSIZ = 20.

NSAMPL = 1000.        BINSIZ = 50.

67. A sensible distribution plot is particularly desirable if the subroutine MINSER is to be used to minimize the chi-square of a fitted normal distribution curves, since the chi-square is dependent on the value of NBIN chosen.

68. KICHCK and INCHCK relate to the option provided for performing a chi-square fit on the calculated factors of safety. This calculation gives a measure of the confidence associated with assuming the factors of safety to be normally distributed. It can give the best estimate of the

distribution of the entire population of factors of safety if they are normally distributed, as distinct from the statistical parameters of the sample values chosen by the Monte Carlo overlay. The allowable value of KICHCK and INCHCK have the following meaning:

KICHCK = 0. no chi-square fit it required

KICHCK = 1. a chi-square fit is required

INCHCK = 0. use default chi-square parameters specified in program

INCHCK = 1. specify chi-square parameters on card H.

69. The value of IPRINT specified here determines the nature of the probabilistic printout.

70. The G Cards specify the distribution of each stochastic variable.

71. STV identifies the variable according to the numbering system given later in the appendix.

72. TYPE defines the type of distribution according to the following code:

TYPE = 1. normal or gaussian

TYPE = 2. triangular

TYPE = 3. uniform or flat

TYPE = 4. truncated normal

TYPE = 5. exponential

TYPE = 6. histogram

73. Either the mean or the mode, depending on which is required for the selected type of distribution, are the values defined in the C, D and E cards. Dispersions are defined by the following:

ST1 - is the standard deviation for a normal or truncated normal distribution, the left cut-off for triangular and flat distributions, the decay constant  $\lambda$  in  $\exp(-x/\lambda)$  or an exponential distribution ( $\lambda$  = average of  $x$  if  $x$  is in the range 0 to  $\infty$ ), and the beginning value of a histogram distribution.

ST2 - is the right cutoff for triangular or flat distributions, the left cutoff for truncated normal and exponential distributions, and the class width for up to 9 classes in a histogram distribution, noting that each class division must have the same width. It should be left blank for a normal distribution.

ST3 - is used only for truncated normal and

exponential distributions to define the right limit. If it is left blank, the right limit will be taken as  $\infty$ , so it should normally be set at least several standard deviations from the mean for a truncated normal distribution.

ST4 - is an array holding the relative frequencies of up to 9 histogram classes. These frequencies are normalized in the program to give a cumulative value of 1.0.

74. Specifying the distributions in this way means that triangular, flat and truncated normal distributions need not be symmetrical about the mean or the mode. Any variable not defined as stochastic is assumed to be deterministic.

75. Note that all cutoffs are specified as being an absolute distance from the values specified on the C, D and E cards, with the exception of the exponential distribution where the inputs are the decay constant and the actual values of the cutoffs.

76. Card H enables the user to specify several control variables affecting the minimization of the chi-square in fitting a normal distribution to the calculated factors of safety. ICON controls the convergence criterion. Possible input values have the following results:

ICON = 1. is the usual input value which results in a relatively high accuracy;  
 ICON = 2. results in a lower accuracy and should not be used unless there is a specific reason why it is acceptable.

77. ESCALE limits the maximum step size in searching combinations of  $\sigma$  and  $\mu$  for a minimum chi-square. ESCALE should usually be 1000., depending on the rate of change of the chi-square as a function of mean and standard deviation.

78. MAXIT is a maximum number of iterations which can be used in minimizing chi-square. MAXIT = 20. should usually be suitable.

79. MINSPR controls the printing of iteration steps to enable the checking of the proper execution for minimizing the chi-square.

MINSPR = 0. No details are printed;

MINSPR = 1. Details of the iteration process in minimizing chi-square are printed out.

80. Details of the method used in the sub-routine MINSER are given in Ref C-3 and C-4.

81. If a sensitivity analysis is desired, ie, if NOSENS > 0., the next inputs are on the I card and consist of the variable number NVAR input as a real number according to the numbering system given in Section 3.4, and NOSTEP, which indicates the number of steps in the sensitivity analysis to a maximum of 40.

82. The next series of cards, the J cards, contains up to 8 values per card which define the values of the parameter being varied. The I and J cards are repeated for each variable for which a sensitivity analysis is desired.

83. The final input card is a continuation control card. The allowable inputs have the following meaning:

NEXT = 0. end of run;

NEXT = 1. new analysis follows, read in new job description card and data (return to card A).

#### Program Options

84. There are four basic program options:

- Deterministic stability analysis: CALCS = 1., NOSENS = 0.
- Deterministic sensitivity analysis: CALCS = 1., NOSENS > 0. and input of sensitivity data
- Probabilistic analysis: CALCS = 0. or -1. and input of probability data
- Sensitivity analysis combined with probabilistic analysis: CALCS = 0. or -1., NOSENS > 0. and input of sensitivity and probability data.

85. It should be emphasized that the automatic sensitivity analysis option is considered most useful for evaluating the effect of physical properties of the rock, the water conditions, and small variations in the wedge geometry. It should be used for varying the wedge height or dip of the face only if the assumption made in scaling the position of the tension crack and the manner in which the water forces are considered are appropriate. Otherwise, each new slope height or dip of the face should be specified as a new problem, with appropriate manual adjustments to the location of the tension crack and to the magnitude of the water force.

### Printed Output

86. The options available for the form of the printed output are specified by the values of IPRINT and JPRINT. IPRINT controls the sensitivity loop printout. Allowable values are as follows:

IPRINT = 0. gives a printout of most of the input information plus many geometric and other intermediate calculations. It also gives a plot of factor of safety versus the parameter being varied for a sensitivity analysis, with the values of the coordinates of each plotted point.

IPRINT = 1. gives only the plot with the values of the parameter being varied and the corresponding factors of safety.

IPRINT = 2. results in the printing of a summary of factors of safety for the different values of the sensitivity variable. This may be adequate if confidence is gained in the use of the program or plotting is not possible.

It should be noted that unless otherwise specified IPRINT will take the value zero.

87. In the case of a probabilistic analysis, the allowable values of JPRINT give the following outputs:

JPRINT = 3. the value of each input parameter selected by the Monte Carlo overlay and used in each calculation of factor of safety is printed out, along with the corresponding factor of safety. For large sample sizes this printout is voluminous. The mean and standard deviation, kurtosis and skewness of the calculated values of factor of safety, and the overall probability of sliding are printed out, along with an ideogram plot of the calculated factors of safety. For combined Monte Carlo - sensitivity runs, the factor of safety and probability of sliding are

plotted against the sensitivity variable.

JPRINT = 4. the output is similar to option 3, except that the values of the individual parameters are not printed.

88. If unspecified, JPRINT takes the default value of 4. Typical output is given in Exhibit C-2. It should be noted that, although only the sample statistics of the calculated factors of safety are determined, the program could readily be modified to calculate the sample statistics and to plot the distributions of any other sampled or calculated parameters. For instance, in an investment analysis it might be required to determine the distribution of volumes of potential sliding masses. If the chi-square curve fitting option is used, a value of MINSPR can be entered as follows:

MINSPR = 1. details of the iteration process in minimizing the chi-square are printed out

MINSPR = 0. no details are printed, this is the default value.

### Other Outputs

89. There are none.

### Flow Charts

90. Figures C-6, C-7 and C-8 are flow charts for WINTAM.

### Sample Problem

91. As part of an investment analysis, a mining company wishes to determine the optimum slope angle in one section of an open pit. As a result of an investigation, it appears that the slope will be in competent rock in which the stability of the slope will be controlled by structural features. Persistent joint sets are found to have the characteristics shown in Table C-1. Normal distributions adequately represent the relevant sampled data. Variable names given in parentheses refer to input variables for program WINTAM.

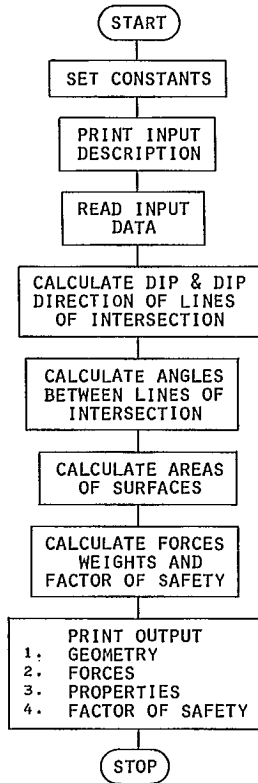


Fig C-6 - Flowchart of basic wedge analysis.

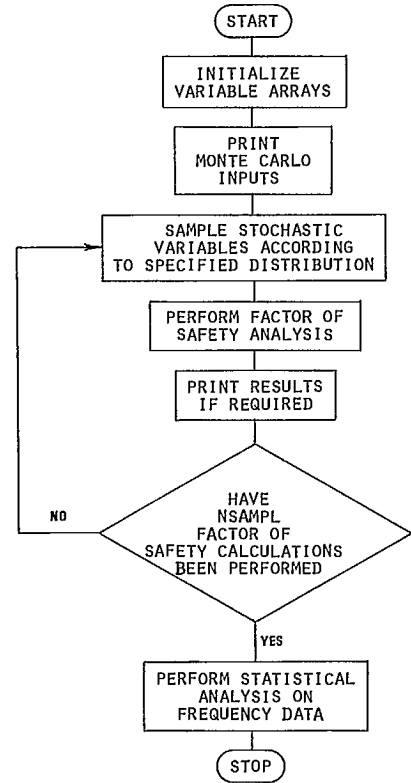


Fig C-7 - Flowchart of Monte Carlo analysis.

Table C-1: Sample problem joint set characteristics

	Joint set A	Joint set B
Mean dip	45° (PHIA)	40° (PHIB)
Standard deviation of dip	3°	4°
Mean dip direction	320° (ALPA)	50° (ALPB)
Standard deviation of dip direction	7°	7°
Mean friction angle	25° (OAF)	32° (OBF)
Standard deviation of friction angle	2°	2°
Mean cohesion	2500 lb/ft <sup>2</sup> (CA) (119.5 kPa)	1000 lb/ft <sup>2</sup> (CB) (47.9 kPa)
Standard deviation of cohesion	500 lb/ft <sup>2</sup> (23.9 kPa)	700 lb/ft <sup>2</sup> (33.5 kPa)
Unit weight of rock	160 lb/ft <sup>3</sup> (DENR) (2.54 t/m <sup>3</sup> )	
Standard deviation of unit weight	5 lb/ft <sup>3</sup> (0.08 t/m <sup>3</sup> )	

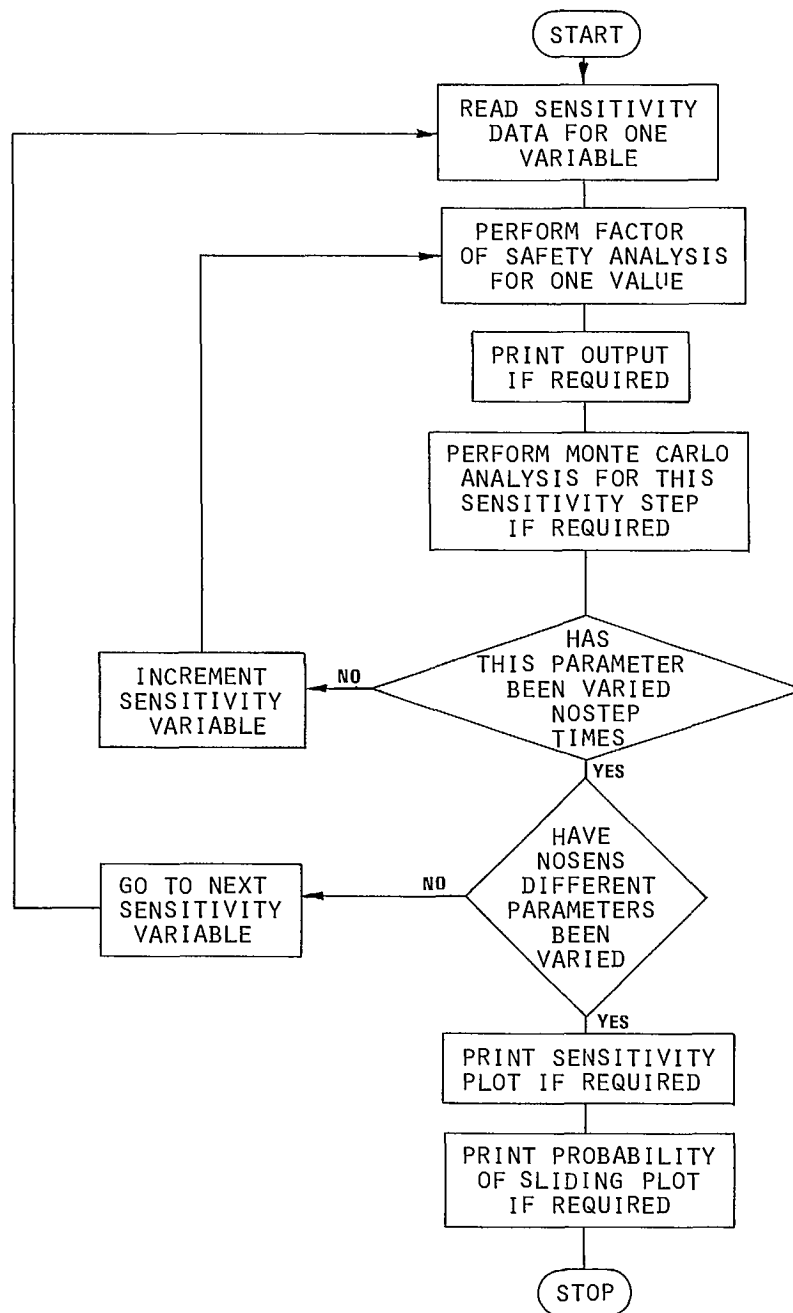


Fig C-8 - Flowchart of sensitivity - Monte Carlo loop.

92. The south wall which dips north ( $ALPH = 0.$ ), is to be examined. It has a horizontal top surface ( $PHIS = 0.$ ,  $ALPS = 0.$ ). Water level observations from piezometers indicate a piezometric line close to the slope surface. This level fluctuates, and some drawdown is indicated near the crest of the pit. A high seasonal rainfall suggests that the piezometric line will remain

high for at least part of each year. The ultimate height of this slope ( $APP$ ) will be 250 ft (76 m). No external forces act on the slope ( $T = 0.$ ,  $PHIT = 0.$ ,  $ALPT = 0.$ ).

#### Procedure

93. A spherical projection analysis, as described earlier in the supplement, shows this to be

a case of potential wedge instability. To analyze the problem, it is necessary to make certain assumptions. For this problem the following assumptions are made:

- a. A persistent joint is taken to infer the presence of single continuous or en echelon joints extending over the height of the slope. Evidence to the contrary could justify the inclusion of a continuity effect which could be incorporated as an increase in cohesion.
- b. The water observations indicated that a nearly maximum hydraulic head is to be expected. Therefore, a water distribution code which varies between the maximum hydraulic head and 90 per cent of maximum is used ( $1.0 \geq \text{PDASHK} \geq 0.9$ ,  $\text{PDASHI} = 0$ ). It should be noted that if the automatic sensitivity analysis is used to vary the slope angle, the same geometric configuration of water distribution will apply for every slope angle.
- c. A tension crack is assumed to form during instability. The location of the tension crack is assumed to be 0.2 times the slope height behind the crest or approximately 50 ft (15 m). The distance from the crest along the trace of Plane A (ATTI) is therefore

$$\frac{50}{\sin 40^\circ} = 78 \text{ ft (24 m)}.$$

For data input, this is rounded off to 80 ft, and the crack is taken to occur at this location when the dip of the slope face is  $50^\circ$ . The tension crack is assumed to be vertical ( $\text{PHIW} = 90$ .) and to strike parallel to the slope face ( $\text{ALPW} = 0$ .). Alternative methods for estimating the location of a potential tension crack could be used.

- d. Because of large coefficients of variation for cohesions, these distributions are truncated at 0. Triangular distributions are applied to the water parameters. All distributions are defined on the Stochastic Variable Data (G) cards. The dip of plane A is specified as being stochastic by specifying its index number as defined beside the wedge diagram on the load sheet ( $\text{STV} = 1$ .). The type of distribution is specified as being normal by inputting the

appropriate Distribution Definition Code for TYPE (TYPE = 1.), and the standard deviation of 3. is specified as described in the table on Stochastic Variable Distribution Definitions ( $\text{STI} = 3$ .). All other stochastic variables are similarly defined by their index numbers, distribution types, variation and, where appropriate, by their limits.

94. All the necessary data on physical properties of the wedge have now been defined, and the remaining input relates to the operation of the program.

95. The Program Control card (B) is used to specify that a probabilistic analysis is to be performed in which the factor of safety is defined as the ratio of driving to resisting forces ( $\text{CALCS} = 0$ .). This card also specifies that one parameter is to be varied in the automatic sensitivity analysis ( $\text{NOSENS} = 1$ .). This parameter is the dip of the slope face (PHIF). A curve showing the probability of sliding for different slope angles is generated automatically. Finally, the B card is used to specify the printout option which determines the level of detail required for the results of the sensitivity analysis. For the print option used ( $\text{IPRINT} = 0$ .) details are obtained of the deterministic stability analysis of the wedge data defined on the C, D and E cards and plots of factor of safety and probability versus the parameter being varied.

96. The following information is all specified on the Monte Carlo Data (F) card: a sample size of 200 for each slope analysis ( $\text{NSAMPL} = 200$ .), the first number of the random number generator of 123 ( $\text{MFIRST} = 123$ .), the number of parameters to be considered stochastic variables ( $\text{NSTV} = 10$ .), and the 20 class intervals for the ideogram plot ( $\text{BINSIZ} = 20$ .). Also specified on this card are that no curve fitting is to be applied to the distribution of outcomes of the Monte Carlo simulation ( $\text{KICHCK} = 0$ .,  $\text{INCHCK} = 0$ .) and JPRINT is specified as 4 to provide a printout for the Monte Carlo process which does not include details of each sample, since the large volume of output is not justified for routine analysis.

97. Since the curve fitting option is not used, the chi-square Data (H) card is not



included. The card is omitted rather than simply left blank.

98. The dip of the face to be varied in the sensitivity analysis (NVAR = 5.) and the five separate dip values to be analyzed (NOSTEP = 5.) are specified on the Sensitivity Control Data (I) card. The five face dip angles to be analyzed, ie, 30., 40., 60., 70., and 80., are specified on the J cards. The base value specified on the C cards is automatically included in the sensitivity analysis and should not be repeated here.

99. Finally, as no more analyses are to be made, this is specified on the Continuation Control (K) card (NEXT = 0.). This completes the input necessary for running the program.

100. The completed data cards and the output generated by the program are given in Exhibit C-2. A description of all input variables is followed by details of the analysis of the base case as defined on the C, D and E cards. The orientations of all lines of intersection and the angles between these lines are printed, as are some of the input data. Calculated weights, areas and volumes are printed for the case with no tension crack and the deduction can caused by the tension crack. For example, the weight of the wedge without a tension crack is 406.37 million lb, but 63.91 million lb lies behind the tension crack in the base case, where the dip of the face (PHIF) is 50°. Wedge depth, which equals 80. in the printout, refers to the distance from the crest to the tension crack along the trace of Plane A. The factor of safety for the base case is also printed.

101. Next, the distributions of all input parameters are printed (TYPE = 0. indicates the parameter is deterministic. The first number for the random number generator, 123, is also printed. A table of all factors of safety calculated in the Monte Carlo process is printed, starting with the value of 0.95829 along with the minimum and maximum calculated factors which are 0.81218 and 1.79497. These factors of safety are printed in an ideogram plot, in which the y-axis is divided into the twenty class intervals specified by BINSIZ, and the number of calculated factors of safety which lie in each class interval is

represented by print characters in the x-direction. The statistics of the calculated factors of safety are also printed out. The plot is seen to represent a reasonable approximation to a normal curve, as is borne out by the values of skewness, 0.043 and kurtosis, 3.18.

102. The final printout for the probabilistic analysis of the base case is the estimated probability of sliding based on the statistics of the calculated factors of safety, 6.40%, and on a direct count of the number of factors of safety falling below the limiting equilibrium condition, 6.50%.

103. The printout from the distributions of input parameters to the estimates of the probability of sliding is then repeated for each new value of PHIF specified in the sensitivity analysis.

104. At low slope angles, many of the geometries sampled define wedges for which the line of intersection does not surface, in which case a factor of safety has no meaning. In such cases, the probability of sliding is estimated only by direct count assuming such wedges to be safe. Extremely high factors of safety can also result when wedges of very small volume are sampled, such as the value of 431.16407 for PHIF = 39. This can arise from driving forces which are very small in relation to the restraining cohesive forces. In this case, the distribution of calculated factors of safety is not normal.

105. The next printout consists of a plot of factor of safety on the x-axis against the parameter varied in the sensitivity analysis, PHIF, on the y-axis, all other parameters being retained at their original base values.

106. The row of asterisks printed for the calculated factor of safety at PHIF = 30° indicates that the line of intersection of the defined wedge does not surface, and wedge instability is therefore not possible.

107. Finally, a plot of probability of sliding along the x axis, as determined by direct count, against the parameter varied in the sensitivity analyses, PHIF in this case, is generated. This plot clearly shows a rapid increase in the probability of instability as the dip of the face increases from 50° to 60°.

## SYSTEM DOCUMENTATION

### Computer Equipment

108. The program was developed on a CDC 6600 and can therefore be run on any similar machine. The pseudo-random number generator used in the Monte Carlo overlay subroutines exploits the word size of CDC equipment. It can be replaced by any of the pseudo-random number generators routinely available in all system libraries.

### Peripheral Equipment

109. Minimum peripheral equipment required are a card reader and line printer.

### Source Program

110. A listing and card deck can be obtained at cost from: Mining Research Laboratories, CANMET, 555 Booth Street, Ottawa, K1A 0G1.

### Variables and Subroutines

111. The following is a list of the variables input into the program and important variables calculated within the program.

Numbers preceding identity variable (NVAR and STV)	Input variables
--	-----------------

1	PHIA = dip of plane A
2	ALPA = dip direction of plane A

3	PHIB = dip of plane B
4	ALPB = dip direction of plane B
5	PHIF = dip of face
6	ALPF = dip direction of face
7	PHIS = dip of top surface
8	ALPS = dip direction of top surface
9	PHIW = dip of tension crack
10	ALPW = dip direction of tension crack
11	APP = vertical height of point A above point at which line of intersection emerges
12	ATTI = distance of tension crack back from the crest along the trace of plane A (distance AT)
13	CA = cohesion on plane A
14	OAF = friction angle on plane A
15	CB = cohesion on plane B
16	OFB = friction angle on plane B
17	DENR = in situ unit weight of rock
18	DENW = unit weight of water
19	T = magnitude of externally applied force
20	PHIT = dip of applied force
21	ALPT = dip direction of applied

	force	tion of chi-square
22	PDASHI = maximum water head expressed as a decimal fraction of the total wedge height	ICON = controls convergence criterion in the minimization of chi-square
23	PDASHK = height of water in the tension crack expressed as a decimal fraction of the total tension crack depth	MAXIT = specifies the maximum number of iterations to be used in the minimization of chi-square
	CALCS = code to define whether analysis is deterministic or probabilistic	MINSR = controls the printing of iteration steps in the minimization of chi-square
	NOSENS = number of parameters to be varied in sensitivity analyses	NVAR = the number of the input parameter, 1 through 23, to be varied during a sensitivity analysis
	IPRINT = printout option code	NOSTEP = number of steps in a sensitivity analysis
	NSAMPL = the number of runs used in the Monte Carlo overlay	S(i) = varying parameter values in a sensitivity analysis
	MFIRST = starting number for random number generator	NEXT = specifies whether the run is complete or if more cases are to follow
	NSTV = number of stochastic variables	
	NBIN = number of sizes of intervals used in frequency plot of Monte Carlo overlay outcomes	
	KICHCK = specifies whether a minimization of the chi-square of a normal distribution fitted to the Monte Carlo overlay outcomes is required	
	INCHCK = specifies whether default values are to be used in the minimization of chi-square	
	STV = parameter identifier	
	TYPE = type of distribution of stochastic variables	
	SD(i) = array to store dispersion parameters ST1, ST2, ST3, as defined on program load sheet (Section 6)	
	ESCALE = determines the search interval in the minimiza-	
		<u>Calculated Variables</u>
		PHII = dip of line i
		ALPI = dip direction of line i
		THEIJ = angle between lines of intersection i and j
		HWEDGE = total height of wedge
		AREAAX = area of plane A
		AREABX = area of plane B
		AREAAY = area of plane A behind tension crack
		AREABY = area of plane B behind tension crack
		AREAT = area of tension crack over which water acts
		HKRAK = height of tension crack
		MTNA = coefficient for resolution of force T in direction normal to plane A
		MTNB = coefficient for resolution of force T in direction normal to plane B
		MWNA = coefficient for resolution of weight in direction normal to plane A
		MWNB = coefficient for resolution of weight in direction normal to plane B
		MVNA = coefficient for resolution of force V in

direction normal to plane A  
 MVNB = coefficient for resolution of force V in  
 direction normal to plane B  
 MNANB = coefficient for resolution of direction  
 NA in direction normal to plane B  
 MT5 = coefficient for resolution of force T  
 along the line of intersection  
 MW5 = coefficient for resolution of weight  
 along the line of intersection  
 MV5 = coefficient for resolution of force V  
 along the line of intersection  
 Q = coefficient of effective normal reaction  
 of weight on plane A  
 R = coefficient of effective normal reaction  
 of force V on plane A  
 S = coefficient of effective normal reaction  
 of T on plane A  
 X = coefficient of effective normal reaction  
 of weight on plane B  
 Y = coefficient of effective normal reaction  
 of force V on plane B  
 Z = coefficient of effective normal reaction  
 of T on Plane B  
 W = weight of the wedge  
 WNTEN = weight of the wedge with no tension crack  
 UANTEN = force on plane A due to water pressure  
 for no-tension-crack case  
 UBNTEN = force on plane B due to water pressure  
 for no-tension-crack case  
 V = force due to water in the tension crack  
 UA = force on plane A due to water pressure  
 for tension-crack case  
 UB = force on plane B due to water pressure  
 for tension-crack case  
 UAA = force on plane A due to water pressure  
 for general case  
 UBB = force on plane B due to water pressure  
 for general case  
 F = factor of safety defined as a ratio  
 FDIFF = factor of safety defined as a difference

#### Subroutines

Main program - controls program operation  
 DESCRP prints description of program inputs  
 INPUTR reads all necessary input data  
 CALCSR controls analysis routines

DIPCAL controls calculation of dip and dip  
 directions of all lines of intersection  
 DIRDIP calculates dip and dip direction of a  
 single intersection  
 ANGCAL controls calculation of angles between  
 all lines of intersection  
 ANGBET calculates angle between two lines  
 ARACAL calculates all required area values  
 KINCAL calculates all forces, weights and the  
 factor of safety  
 PRINTR prints all normal program output for  
 basic stability analysis  
 SENSOT generates sensitivity data plot on the  
 line printer  
 TSORT sorts sensitivity input data in ascending  
 order  
 MONTE links the deterministic section of the  
 program with the Monte Carlo overlay  
 SAMPLE links Monte Carlo with the various  
 sampling subroutines  
 RANDOM generates pseudo-random numbers using the  
 congruence method  
 GAUSS uses the central limit theorem to sample  
 a random variable with a Gaussian  
 distribution  
 TRIDIS samples a random variable with a triang-  
 ular distribution  
 STATAN is a driver subroutine for the ideogram  
 plot and statistical analysis subroutines  
 STATO1 determines mean, standard deviation,  
 skewness and kurtosis of the calculated  
 factors of safety, and links to the  
 chi-square routines  
 FRQTBL computes frequencies of factor of safety  
 for a specified number of class intervals  
 IDGPLT1 plots an ideogram of calculated factors  
 of safety  
 P (X) this function determines the area beneath  
 a normal distribution curve from 0 to X,  
 using Hasting's approximation  
 CHISQR this function calculates Person's  
 chi-square  
 MINSER minimizes the chi-square by varying the  
 values of mean and standard deviation  
 used in finding the most probable  
 Gaussian distribution of the calculated  
 factors of safety

PFPL0T plots the probability of sliding against the parameter being varied in a probability-sensitivity analysis

and library subroutines for arcsine (ASIN), cosine (COS), sine (SIN), square root (SQRT), tangent (TAN), arctangent (ATAN), arctangent ( $x_1/x_2$ ) (ATAN2), arcosine (ACOS).

#### Storage Requirements

112. 43,000 octal words on the CDC 6000 or CYBER.

#### Maintenance and Updates

113. Probabilistic analysis added November 1974. Program modularized and updated October 1975.

## OPERATING DOCUMENTATION

### Operating Instructions

114. There are no special operating instructions for this program.

### Operating Messages

115. There are no special messages produced by the program.

### Control Cards

116. Standard compile and execute cards are all that are required to run the program.

### Error Recovery

117. Not applicable.

### Run Time

118. Each factor of safety calculation requires .03 seconds of CDC 6600 CPU time. The Monte Carlo documentation gives additional information for estimating total run time. The sample problem took 20 CP seconds to run at a cost of about \$5.60.

EXHIBIT C-1





## DATA INPUT

### A. Header card Format (A10,A3,A6,A61)

Job number  
User's initials  
Date  
Title

### B. Control card Format (8F10.0)

CALCS - method of analysis.

-1. = Probabilistic analysis with factor of safety defined as difference.

0. = Probabilistic analysis with factor of safety defined as ratio.

1. = conventional factor of safety analysis.

NOSENS - number of parameters to be varied in sensitivity analysis.

IPRINT - print control

0. = Prints input, intermediate calculations and sensitivity analysis plot.

1. = Gives only sensitivity analysis plot.

2. = Prints summary table of results only.

### C. Wedge geometry data

Refer to Fig C-1. Numbers in parentheses are index numbers of the variables.

### Card C1 Format (8F10.0)

PHIA(1) Dip of plane A  
ALPA(2) Dip direction of plane A  
PHIB(3) Dip of plane B  
ALPB(4) Dip direction of plane B  
PHIF(5) Dip of face  
ALPF(6) Dip direction of face  
PHIS(7) Dip of top surface  
ALPS(8) Dip direction of top surface

### Card C2 Format (4F10.0)

PHIW(9) Dip of tension crack.  
ALPW(10) Dip direction of tension crack  
APP(11) Vertical height of point A above point at which line of intersection emerges.  
ATTI(12) Distance from point A to tension crack; this must be considered deterministic.

### D. Physical property data Format (6F10.0)

Numbers in parentheses are index numbers of the variables.

CA(13) Cohesion on plane A.  
OAF(14) Friction angle on plane A.  
CB(15) Cohesion on plane B.  
OBF(16) Friction angle on plane B.

DENR(17) In situ unit weight of rock.  
 DENW(18) Unit weight of water.

E. Force data Format (5F10.0)

T(19) Magnitude of externally applied force.  
 PHIT(20) Dip of applied force.  
 ALPT(21) Dip direction of applied force.  
 PDASHI(22) Maximum water head expressed as a decimal fraction of total wedge height.  
 PDASHI(23) Height of water in tension crack expressed as a decimal fraction of total tension crack depth.

Note: the input of water distribution is governed by the following:

ATTI=-1. PDASHI=0.0 No tension crack, dry slope.  
 ATTI=-1. PDASHI=0.5 No tension crack, saturated slope.  
 ATTI=-1. PDASHI=1.0 No tension crack, saturated slope with impermeable face.  
 ATTI>0. PDASHK=0.0 Tension crack, dry slope.  
 ATTI>0. PDASHK=1.0 Tension crack, saturated slope.  
 ATTI>0. PDASHI=0.5 Water level at bottom of tension crack.  
 ATTI>0. PDASHI<0.5 Water level below bottom of tension crack.

Values between 0.0 and 1.0 for PDASHI and PDASHK correspond to varying degrees of saturation.

Non-zero values of PDASHI and PDASHK must not be input simultaneously

F. Monte Carlo control data Format (7F10.0)

Skip cards F, G and H if CALCS on card A is greater than 0.

NSAMPL - Number of samples.  
 MFIRST - Seed for random number generator.  
 NSTV - Number of stochastic variables.  
 BINSIZ - Class interval for ideogram plot if < 1.

- Number of classes for ideogram plot if  $\geq 1$ .

KICHCK  $\leq 0$ . No chi-square fit required.  
 $\geq 1$ . Chi-square fit required.

INCHICK  $\leq 0$ . Use default chi-square parameters.  
 $\geq 1$ . Specify chi-square parameters on line H

JPRINT - Probability analysis print control.  
 3. = Prints frequency plot, statistical information and all parameter values chosen by Monte Carlo overlay.  
 4. = Prints frequency plot, statistical information and basic input values. This is the default value for probabilistic analysis.

G. Stochastic variable data - repeat NSTV times each card Format (F2.0,F3.0,3F10.0,9F5.0)

STV - index number of variable for which stochastic parameters are input.

TYPE - type of distribution control.  
 for type = 1,2,3,4 or 5 see Fig C-9;  
 for type = 6 see Fig C-10.

ST1 - standard deviation.  
 ST2 - other distribution parameter.  
 ST3 - other distribution parameter.  
 ST4(I), I=1,9 - relative frequencies of histogram classes.

H. Chi-square data Format (4F10.0)

Skip card H if INCHCK on card F is less than 1. Refer to appendix text for description of variables.

ESCALE  
 ICON  
 MAXIT  
 MINSPR

I. Sensitivity control card Format (2F10.0)

Repeat cards I and J NOSENS times - see card A.

NVAR - index of parameter to be varied.  
 NOSTEP - number of different values to be taken by variable NVAR in the sensitivity analysis. Do not use basic input value for NVAR as this is automatically included in

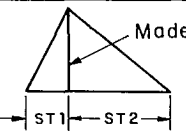
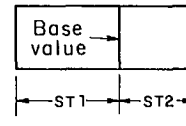
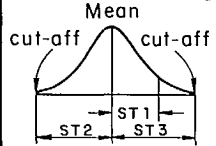
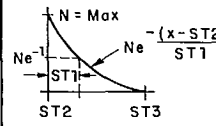
TYPE	ST 1	ST 2	ST 3
1.	Standard deviation	blank	blank
2.	Maximum distance from the made to the left (lower) side (positive distance)	Maximum distance from the made to the right (upper) side.	blank 
3.	Maximum distance from the base input value to the left (lower) side (positive distance)	Maximum distance from the base input value to the right (upper) side	blank 
4.	Standard deviation 	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side.
5.	Decay constant 	Lower bound Measured from 0	Upper bound Measured from 0

Fig C-9 - Input data for stochastic variables according to distribution type.

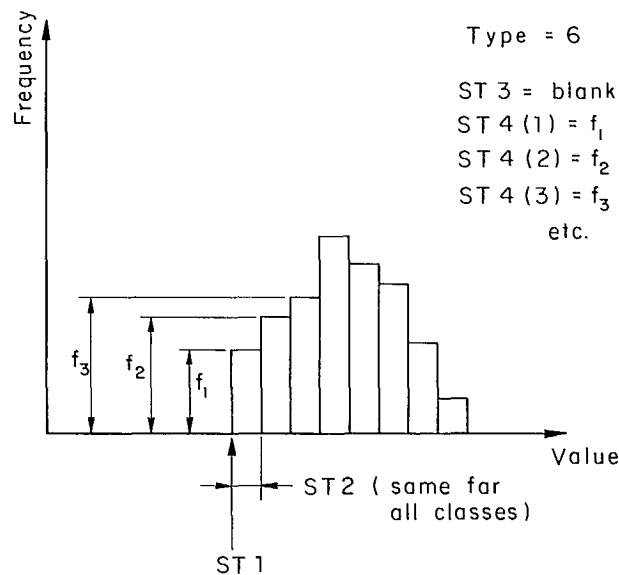


Fig C-10 - Input data for histogram distribution.

the sensitivity analysis.

A.

J. Sensitivity values for variable NVAR. NOSTEP  
values (up to 40) Format (8F10.0)  
(up to 5 cards allowed)  
S(I), I=1, NOSTEP  
repeat cards I and J NOSENS times - see card

K. Continuation control Format (F10.0)

NEXT

0. = all runs complete

1. = another job follows - go to card A.

EXHIBIT C-2



## INPUT

1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

[illegible]

## EXAMPLE OUTPUT DATA

### DESCRIPTION OF PROGRAM INPUT VARIABLES

#### BASIC WEDGE INPUT DATA

PHIA = DIP OF PLANE A  
 ALPA = DIP DIRECTION OF PLANE A  
 PHIB = DIP OF PLANE B  
 ALPB = DIP DIRECTION OF PLANE B  
 PHIF = DIP OF FACE  
 ALPF = DIP DIRECTION OF FACE  
 PHIS = DIP OF TOP SURFACE  
 ALPS = DIP DIRECTION OF TOP SURFACE  
 PHIW = DIP OF TENSION CRACK  
 ALPW = DIP DIRECTION OF TENSION CRACK  
 APP = VERTICAL HEIGHT OF POINT A ABOVE POINT AT WHICH LINE OF INTERSECTION DAYLIGHTS  
 ATTI = DISTANCE FROM POINT A TO TENSION CRACK  
 CA = COHESION ON PLANE A  
 OAF = FRICTION ANGLE ON PLANE A  
 CB = COHESION ON PLANE B  
 OBF = FRICTION ANGLE ON PLANE B  
 DENR = IN SITU UNIT WEIGHT OF ROCK  
 DENW = UNIT WEIGHT OF WATER  
 T = MAGNITUDE OF EXTERNALLY APPLIED FORCE  
 PHIT = DIP OF APPLIED FORCE  
 ALPT = DIP DIRECTION OF APPLIED FORCE  
 POASHI = MAX. WATER HEAD EXPRESSED AS A DECIMAL FRACTION OF TOTAL WEDGE HEIGHT  
 POASHK = HEIGHT OF WATER IN TENSION CRACK EXPRESSED AS A DECIMAL FRACTION OF TOTAL TENSION CRACK DEPTH

#### MNTE CARLO INPUT DATA

CALCS = MONTE CARLO/DETERMINISTIC CONTROL FLAG  
 NSAMPL = NO OF TRIALS FOR MONTE CARLO ANALYSIS  
 MFIRST = STARTING ODD NUMBER FOR RANDOM NUMBER GENERATOR  
 NSTV = NO OF STOCHASTIC VARIABLES  
 NBIN = NO OF INTERVALS FOR FREQUENCY PLOT  
 KICCHK = CHI-SQUARE CONTROL FLAG  
 INCHKC = CHI-SQUARE PARAMETER CONTROL FLAG  
 STV = STOCHASTIC VARIABLE NUMBER  
 TYPE = SAMPLING DISTRIBUTION TYPE CONTROL FLAG  
 SD1 = STANDARD DEVIATION FOR GAUSSIAN DISTRIBUTION, LEFT CUTOFF FOR OTHER DISTRIBUTIONS  
 SD2 = RIGHT CUTOFF FOR TRIANGULAR AND UNIFORM DISTRIBUTION, LEFT CUTOFF FOR CUTOFF GAUSSIAN DISTRIBUTION  
 SD3 = RIGHT CUTOFF FOR CUTOFF GAUSSIAN DISTRIBUTION  
 SD4 = HISTOGRAM DEFINING STOCHASTIC VARIABLE  
 ESCALE = LIMITS MAXIMUM STEP-SIZE IN CHI-SQUARE MINIMIZATION  
 ICDN = CONTROLS CHI-SQUARE CONVERGENCE CRITERIA  
 MAXIT = MAXIMUM NO OF ITERATIONS FOR CHI-SQUARE MINIMIZATION  
 MINSPR = CONTROLS PRINTING OF CHI-SQUARE MINIMIZATION DATA

#### SENSITIVITY INPUT DATA

NOSENS = NO OF SENSITIVITY VARIABLES  
 NVAR = VARIABLE NO FOR THIS SENSITIVITY RUN  
 NOSTEP = NO OF VARIATIONS IN THE VARIABLE FOR THIS SENSITIVITY RUN  
 SAVE = TABLE OF VARIATIONS FOR THIS SENSITIVITY RUN

#### GENERAL INPUT DATA

IPRINT = PRINT CONTROL FLAG  
 NEXT = PROGRAM CONTINUATION CONTROL FLAG  
 IDENT = ANALYSIS DESCRIPTION INFORMATION



## 3-D ROCK WEDGE STABILITY ANALYSIS

1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

## DIP DIRECTIONS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	320.00	9.07	270.00	50.00	324.08
PLANE B		50.00	90.00	320.00	45.42
TENSION CRACK T			0.00	90.00	
UPPER SLOPE S				-0.00	90.00
SLOPE FACE F					0.00

## DIPS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	44.06	32.37	31.88	0.00	43.98
PLANE B		40.00	32.73	0.00	39.91
TENSION CRACK T			90.00	0.00	
UPPER SLOPE S				-0.00	0.00
SLOPE FACE F					50.00

## ANGLES BETWEEN LINES OF INTERSECTION

PLANES LINE	LINE	4	5	7	8	9
A S	3	90.0	50.4	130.6		
B S	4		56.4		122.7	130.0
A B	5			80.2	66.3	
A T	7					148.1
B T	8					32.7
S T	9					

PLANES LINE	3	4	5
A F	1	87.1	36.7
B F	2		86.5
			30.1

PLANE A HAS COHESION 2500. AND FRICTION ANGLE 25.0

PLANE B HAS COHESION 1000. AND FRICTION ANGLE 32.0

ASSUMED ROCK DENSITY IS 160.00 WATER DENSITY 62.40

WEDGE HEIGHT	WEDGE DEPTH	WEDGE WEIGHT	WEDGE VOLUME
250.00	80.00	436.99 - 73.31 (XE06)	273.12 - 45.82 (XE04)

AREA PLANE A	AREA PLANE B	AREA PLANE T
50242.- 11808.	45607.- 10719.	10719.

## COEFFICIENTS FOR DETERMINATION OF EFFECTIVE NORMAL REACTIONS

	DIRECTION A	DIRECTION B
FORCE W	.43	.53
FORCE V	-.44	-.17
FORCE T	0.00	0.00

CASE 4 - TENSION CRACK - WATER HEIGHT 82.

WEDGE DEPTH 80.

FACE DIP DIRECTION = 0.0 WEDGE HEIGHT = 250. FACTOR OF SAFETY = 1.192

## 1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

## RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	50.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SD1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
SD2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIH	ALPH	APP	ATTI	CA	DAF	CB	0BF
AVG	90.00	0.00	250.00	80.00	2500.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
SD1	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
SD2	0.00	0.00	0.00	0.00	2500.00	0.00	1000.00	0.00
SD3	0.00	0.00	0.00	0.00	3000.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	DENR	DENH	T	PHIT	ALPT	POASHI	POASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
SD1	5.00	0.00	0.00	0.00	0.00	0.00	0.00
SD2	0.00	0.00	0.00	0.00	0.00	0.00	.10
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST= 123

## SAMPLE VALUES FOR FACTOR OF SAFETY

1.02314	1.24560	1.04373	1.36857	1.17465	1.21415	1.40984	1.12431	1.19403	.98173
1.16889	1.27262	1.43668	1.33419	1.61180	1.28329	1.32478	1.48505	.98191	1.46196
1.06409	.95724	1.03221	1.06677	1.17045	1.39549	1.12784	1.13733	1.01799	1.01122
1.21884	1.56672	1.23537	1.14029	1.30950	1.61110	1.40977	1.31225	.88555	1.30519
.97714	1.29552	1.26534	1.21212	1.25539	1.18290	1.18124	1.14681	1.21811	1.12148
1.23158	1.00446	1.14137	1.02555	1.31473	1.30351	1.25541	1.22432	1.10510	1.26221
.99662	1.55594	.95155	1.11106	1.33269	1.14144	1.01719	1.15628	1.28878	1.46993
1.37118	1.46722	1.18183	1.11995	1.13384	1.23410	.98864	1.44673	1.13348	1.12592
1.01427	1.26556	1.06547	1.07541	1.20235	1.28815	1.39220	1.61275	1.03740	1.18688
1.17497	1.34437	1.21557	1.34377	1.05885	1.23429	1.39759	1.36256	1.26308	1.33883
1.14352	1.23416	1.13028	1.03931	1.41933	1.04144	1.51472	1.19589	1.53695	1.13249
1.30143	1.01064	1.48851	1.42094	.96224	1.14727	.98689	1.12534	1.10966	1.54254
1.29574	1.14011	1.42849	1.30105	1.04468	1.06365	1.57222	1.26199	1.37300	1.08718
1.42634	.89077	1.29642	1.31527	1.12382	1.42209	1.51672	1.32267	1.29468	1.27425
1.28083	1.23414	1.11333	1.37113	1.12248	1.19608	1.19312	1.10569	1.17100	1.33983
1.07820	1.35666	1.16614	1.32221	1.04026	1.04735	1.30938	1.18644	1.08328	.87856
1.24301	1.29762	1.59895	1.04410	.96581	1.14820	1.17570	1.02249	1.18297	1.34621
1.48597	1.17094	1.34990	.94109	1.60321	1.19460	1.11046	1.28995	1.53091	1.38127
1.20676	1.21888	1.71132	1.49869	.93078	1.06267	1.33497	1.06896	1.18015	1.51704
1.36223	1.30234	1.24572	1.38423	1.22635	1.20714	1.67364	1.12098	1.21860	1.27651

MIN F.S.= .87856 MAX F.S.= 1.71132

-----  
 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS	INTERVAL	0	10	20	30	40	50	60	70	80	90	100	FREQ	PCT
1	.88	.92	XXX										3	1.5
2	.92	.96	XXXX										4	2.0
3	.96	1.00	XXXXXXXX										8	4.0
4	1.00	1.05	XXXXXXXXXXXXXX										17	8.5
5	1.05	1.09	XXXXXXXXXX										11	5.5
6	1.09	1.13	XXXXXXXXXXXXXX										16	8.0
7	1.13	1.17	XXXXXXXXXXXXXX										16	8.0
8	1.17	1.21	XXXXXXXXXXXXXX										22	11.0
9	1.21	1.25	XXXXXXXXXXXXXX										17	8.5
10	1.25	1.29	XXXXXXXXXXXXXX										16	8.0
11	1.29	1.33	XXXXXXXXXXXXXX										20	10.0
12	1.33	1.37	XXXXXXXXXXXXXX										13	6.5
13	1.37	1.41	XXXXXX										8	4.0
14	1.41	1.45	XXXXXX										6	3.0
15	1.45	1.49	XXXXXX										7	3.5
16	1.49	1.53	XXXXXX										6	3.0
17	1.53	1.57	XXX										3	1.5
18	1.57	1.61	XXXX										5	2.5
19	1.61	1.65	X										0	0.0
20	1.65	1.69	XX										2	1.0

-----  
 SAMPLE STATISTICS  
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MEAN= 1.231 S.D.= .171 SKEWNESS= .144 KURTOSIS= 2.74 SAMPLE SIZE= 200

-----  
 PROBABILITY OF SLIDING  
 -----

P.F.= 0.85 X BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = 1.231 AND S.D. DEV. = .171  
 P.F.= 7.58 X BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 0

### 3-D ROCK WEDGE STABILITY ANALYSIS

1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

SLIDING IS KINEMATICALLY IMPOSSIBLE FOR THE FOLLOWING INPUT DATA

\*\*\*\*\*

#### DIP DIRECTIONS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	320.00	9.07	270.00	50.00	14.76
PLANE B		50.00	90.00	320.00	3.38
TENSION CRACK T			0.00	90.00	
UPPER SLOPE S				-0.00	90.00
SLOPE FACE F					0.00

#### DIPS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	44.06	32.37	31.88	0.00	29.17
PLANE B		40.00	32.73	0.00	29.96
TENSION CRACK T			90.00	0.00	
UPPER SLOPE S				-0.00	0.00
SLOPE FACE F					30.00

## 1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

## RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	30.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SD1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
SD2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIW	ALPW	APP	ATTI	CA	OAF	CB	OBF
AVG	90.00	0.00	250.00	80.00	2500.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
SD1	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
SD2	0.00	0.00	0.00	0.00	2500.00	0.00	1000.00	0.00
SD3	0.00	0.00	0.00	0.00	3000.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	DENR	DENW	T	PHIT	ALPT	PDASHI	PDASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
SD1	5.00	0.00	0.00	0.00	0.00	0.00	0.00
SD2	0.00	0.00	0.00	0.00	0.00	0.00	.10
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST= 123

## SAMPLE VALUES FOR FACTOR OF SAFETY

6.89202	21.88757	6.895922529	4.8687	8.61332	3.03835	36.07747	3.92682	3.30189	6.27234
26.89431	5.68679	17.03242	8.86235	33.71685	21.36430	3.78399	2.53983	3.57532	2.79044
6.97816	3.63276	19.99665	4.71145	23.04940	4.94515	4.96921	5.16666	27.94754	4.02901
7.88712	3.09680	6.90380							

MIN F.S.= 2.53983 MAX F.S.=2525.48687

## FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES

CLASS	INTERVAL	0	10	20	30	40	50	60	70	80	90	100	FREQ	PER
1	2.54	124.00	124.00	124.00	124.00	124.00	124.00	124.00	124.00	124.00	124.00	124.00	32	97.0
2	124.00	255.23	255.23	255.23	255.23	255.23	255.23	255.23	255.23	255.23	255.23	255.23	0	0.0
3	255.23	301.58	301.58	301.58	301.58	301.58	301.58	301.58	301.58	301.58	301.58	301.58	0	0.0
4	301.58	507.53	507.53	507.53	507.53	507.53	507.53	507.53	507.53	507.53	507.53	507.53	0	0.0
5	507.53	634.24	634.24	634.24	634.24	634.24	634.24	634.24	634.24	634.24	634.24	634.24	0	0.0
6	634.24	749.62	749.62	749.62	749.62	749.62	749.62	749.62	749.62	749.62	749.62	749.62	0	0.0
7	749.62	886.37	886.37	886.37	886.37	886.37	886.37	886.37	886.37	886.37	886.37	886.37	0	0.0
8	886.37	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	97101.32	0	0.0
9	97101.32	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	101139.67	0	0.0
10	101139.67	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	1266.01	0	0.0
11	1266.01	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	111392.36	0	0.0
12	111392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	121392.36	0	0.0
13	121392.36	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	131519.71	0	0.0
14	131519.71	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	141645.06	0	0.0
15	141645.06	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	151771.40	0	0.0
16	151771.40	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	161897.75	0	0.0
17	161897.75	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	172024.10	0	0.0
18	172024.10	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	182150.45	0	0.0
19	182150.45	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	192276.79	0	0.0
20	192276.79	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	202403.14	0	0.0
21	202403.14	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	212529.49	1	3.0

## SAMPLE STATISTICS

MEAN=87.150 S.D.=\*\*\*\*\* SKEWNESS=29.984 KURTOSIS= 31.00 SAMPLE SIZE= 33

## PROBABILITY OF SLIDING

P.F.= 0.00 % BY COUNTY WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
\*\*\*NUMBER OF SUCH CASES WERE 167

## 3-D ROCK WEDGE STABILITY ANALYSIS

1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

## DIP DIRECTIONS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	320.00	9.07	270.00	50.00	351.06
PLANE B		50.00	90.00	320.00	25.00
TENSION CRACK T			0.00	90.00	
UPPER SLOPE S				-0.00	90.00
SLOPE FACE F					0.00

## DIPS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	44.06	32.37	31.88	0.00	39.66
PLANE B		40.00	32.73	0.00	37.25
TENSION CRACK T			90.00	0.00	
UPPER SLOPE S				-0.00	0.00
SLOPE FACE F					40.00

## ANGLES BETWEEN LINES OF INTERSECTION

PLANE LINE	4	5	7	8	9
A S	3	90.0	50.4	130.6	
B S	4		56.4	122.7	130.0
A B	5			66.3	
A T	7				148.1
B T	8				32.7
S T	9				

PLANE LINE	3	4	5
A F	1	66.6	16.2
B F	2		70.3

PLANE A HAS COHESION 2500. AND FRICTION ANGLE 25.0

PLANE B HAS COHESION 1000. AND FRICTION ANGLE 32.0

ASSUMED ROCK DENSITY IS 160.00 WATER DENSITY 62.40

WEDGE HEIGHT	WEDGE DEPTH	WEDGE WEIGHT	WEDGE VOLUME
250.00	40.74	113.33 - 9.68 (XE06)	70.83 - 6.05 (XE04)

AREA PLANE A	AREA PLANE B	AREA PLANE T
25586.- 3062.	23226.- 2780.	2780.

## COEFFICIENTS FOR DETERMINATION OF EFFECTIVE NORMAL REACTIONS

	DIRECTION A	DIRECTION B
FORCE W	.43	.53
FORCE V	-.44	-.17
FORCE T	0.00	0.00

CASE 4 - TENSION CRACK - WATER HEIGHT 42.

WEDGE DEPTH 41.

FACE DIP DIRECTION = 0.0 WEDGE HEIGHT = 250. FACTOR OF SAFETY = 1.925

## 1234567890RS 040177 3-0 WEDGE EXAMPLE ANALYSIS

## RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	40.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SD1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
SD2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIW	ALPH	APP	ATTI	CA	OAF	CB	OBF
AVG	90.00	0.00	250.00	80.00	2500.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
SD1	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
SD2	0.00	0.00	0.00	0.00	2500.00	0.00	1000.00	0.00
SD3	0.00	0.00	0.00	0.00	3000.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	DENR	DENW	T	PHIT	ALPT	PDASHI	PDASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
SD1	5.00	0.00	0.00	0.00	0.00	0.00	0.00
SD2	0.00	0.00	0.00	0.00	0.00	0.00	.10
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST= 123

## SAMPLE VALUES FOR FACTOR OF SAFETY

2.30791	1.99269	1.49507	1.80393	1.84752	2.28013	3.24160	1.61489	1.64865	2.23049
1.50426	1.80822	3.24594	1.90651	3.45220	1.86343	2.20975	4.46139	1.50290	2.01566
1.60501	3.41902	1.67674	2.13401	2.53488	790.39428	3.87562	2.20416	1.25789	1.40738
1.64476	3.13325	2.50708	2.22838	2.22105	1.98233	2.20277	3.22019	1.55421	1.90083
1.44057	2.71633	2.06600	3.50993	3.36867	1.82943	2.30885	3.50602	1.74913	1.77115
2.37486	1.83389	3.28231	1.53853	1.59475	1.74616	1.92959	1.85469	1.71969	1.96540
1.53831	2.42579	1.73727	1.89791	2.13136	2.19168	1.97379	4.57957	2.46756	5.44956
1.94481	2.12276	1.96163	1.88327	1.88256	2.13191	8.20588	4.87490	1.74359	1.47116
1.34649	3.22013	1.53658	1.90802	2.72046	2.81571	3.51177	2.81230	2.25984	3.63607
2.47621	2.01082	1.62028	3.22396	6.00004	1.86952	2.45547	2.98181	1.85397	2.02706
1.86131	1.75167	2.30414	1.56180	2.49870	2.30557	2.05598	1.86638	2.86186	3.75275
1.64988	1.41649	3.37290	1.78071	1.67003	1.99116	1.73343	2.35683	1.91639	1.77568
1.90127	2.12589	2.28365	1.91230	2.39631	1.89368	3.38876	1.85256	4.42987	2.33848
2.39439	1.59443	1.61924	2.71428	2.15783	1.68541	4.13209	2.25904	1.92568	2.62875
2.13005	1.82898	2.00119	1.78019	1.88206	1.47905	1.61434	1.87785	1.88086	1.92301
1.39171	2.80647	1.59045	2.03915	2.08245	1.81655	1.68610	2.19406	1.97073	2.59932
1.99017	2.68684	14.51841	1.55804	1.60972	2.05863	3.34381	1.30915	2.01052	3.16936
4.43864	2.38421	5.82686	1.43684	2.05852	1.85207	2.33212	2.93916	5.00594	2.00309
1.68659	3.68909	2.12140	2.94590	1.38883	1.53051	1.90784	2.80523	2.05168	2.95545
34.22893	1.81778	1.65902	1.68020	1.75925	1.53736	4.13437	1.61832	6.90034	1.89405

MIN F.S.= 1.25789 MAX F.S.= 790.39428

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 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
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CLASS	INTERVAL	FREQ	PCT
1	1.26 40.71	199	99.5
2	40.71 80.17	0	0.0
3	80.17 119.63	0	0.0
4	119.63 159.09	0	0.0
5	159.09 198.54	0	0.0
6	198.54 238.00	0	0.0
7	238.00 277.46	0	0.0
8	277.46 316.91	0	0.0
9	316.91 356.37	0	0.0
10	356.37 395.83	0	0.0
11	395.83 435.28	0	0.0
12	435.28 474.74	0	0.0
13	474.74 514.20	0	0.0
14	514.20 553.65	0	0.0
15	553.65 593.11	0	0.0
16	593.11 632.57	0	0.0
17	632.57 672.02	0	0.0
18	672.02 711.48	0	0.0
19	711.48 750.94	0	0.0
20	750.94 790.40	1	.5

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 SAMPLE STATISTICS  
 MEAN= 6.510 S.D.=55.768 SKEWNESS=\*\*\*\*\* KURTOSIS=197.14 SAMPLE SIZE= 200  
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 PROBABILITY OF SLIDING  
 P.F.= 46.06 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = 6.510 AND STD. DEV. =55.768  
 P.F.= 0.00 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 0  
 -----

### 3-D ROCK WEDGE STABILITY ANALYSIS

1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

#### DIP DIRECTIONS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	320.00	9.07	270.00	50.00	302.12
PLANE B		50.00	90.00	320.00	61.68
TENSION CRACK T			0.00	90.00	
UPPER SLOPE S				-0.00	90.00
SLOPE FACE F					0.00

#### DIPS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	44.06	32.37	31.88	0.00	42.64
PLANE B		40.00	32.73	0.00	39.41
TENSION CRACK T			90.00	0.00	
UPPER SLOPE S				-0.00	0.00
SLOPE FACE F					60.00

#### ANGLES BETWEEN LINES OF INTERSECTION

PLANES LINE	4	5	7	8	9
A S 3	90.0	50.4	130.6		
B S 4		56.4		122.7	130.0
A B 5			80.2	66.3	
A T 7					148.1
B T 8					32.7
S T 9					

PLANES LINE	3	4	5
A F 1	103.1		52.7
B F 2		99.0	42.6

PLANE A HAS COHESION 2500. AND FRICTION ANGLE 25.0  
 PLANE B HAS COHESION 1000. AND FRICTION ANGLE 32.0

ASSUMED ROCK DENSITY IS 160.00 WATER DENSITY 62.40

WEDGE HEIGHT	WEDGE DEPTH	WEDGE WEIGHT	WEDGE VOLUME
250.00	109.14	813.30 - 186.13 (XE06)	508.31 - 116.33 (XE04)

AREA PLANE A 68541.- 21977.  
 AREA PLANE B 62218.- 19950.  
 AREA PLANE T 19950.

#### COEFFICIENTS FOR DETERMINATION OF EFFECTIVE NORMAL REACTIONS

	DIRECTION A	DIRECTION B
FORCE W	.43	.53
FORCE V	-.44	-.17
FORCE T	0.00	0.00

CASE 4 - TENSION CRACK - WATER HEIGHT 112.

WEDGE DEPTH 109.

FACE DIP DIRECTION = 0.0 WEDGE HEIGHT = 250. FACTOR OF SAFETY = .973

## 1234567890RS 040177 3-D WEDGE EXAMPLE ANALYSIS

## RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	60.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SD1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
SD2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIH	ALPH	APP	ATTI	CA	OAF	CB	OBF
AVG	90.00	0.00	250.00	80.00	2500.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
SD1	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
SD2	0.00	0.00	0.00	0.00	250.00	0.00	1000.00	0.00
SD3	0.00	0.00	0.00	0.00	300.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	DENR	DENH	T	PHIT	ALPT	PDASHI	PDASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
SD1	5.00	0.00	0.00	0.00	0.00	0.00	0.00
SD2	0.00	0.00	0.00	0.00	0.00	0.00	.10
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST=

123

## SAMPLE VALUES FOR FACTOR OF SAFETY

.77400	1.00863	.89562	1.18857	.97828	.94814	1.01769	.95489	1.01872	.74843
1.03110	1.08278	1.05867	1.12436	1.21228	1.06760	1.07047	1.05005	.82399	1.23363
.87975	.68686	.84922	.83002	.89610	.85190	.81536	.89408	.90938	.87029
1.05404	1.18522	.95159	.88899	1.04011	1.43734	1.13740	.94907	.71848	1.08717
.83264	.96476	1.02427	.87324	.91726	.97519	.91721	.82092	1.02344	.91783
.95251	.80073	.82024	.85098	1.18477	1.11753	1.02603	1.01221	.91681	1.02438
.82082	1.24677	.75783	.89616	1.08191	.90072	.81034	.79389	.98483	1.01873
1.16173	1.21783	.94931	.90094	.91325	.97670	.66293	1.01143	.92999	.98161
.89431	.91860	.90541	.86075	.90474	.98498	1.00965	1.24621	.79840	.85309
.90873	1.12329	1.05585	1.03715	.72377	1.02171	1.10589	1.00305	1.04945	1.10289
.92503	1.04694	.86127	.86565	1.11498	.79922	1.29392	.97471	1.18016	.80203
1.16349	.85294	1.08517	1.25450	.78367	.93057	.78901	.86047	.88960	1.41861
1.07290	.88720	1.15224	1.08250	.78814	.86133	1.17556	1.05226	.94850	.85074
1.14669	.72508	1.14924	.99318	.88695	1.29073	1.11032	1.06034	1.07153	.97221
1.01210	1.04071	.88477	1.20207	.90176	1.06940	1.03004	.89367	.94761	1.12439
.94460	1.00784	1.00229	1.08192	.81688	.84585	1.14616	.93266	.84725	.66417
1.01098	.98042	1.02547	.88771	.77596	.91252	.86345	.90260	.94385	.99804
1.04108	.89196	.92520	.79313	1.40187	.98796	.85539	.96397	1.06738	1.15278
1.02158	.87653	1.51525	1.15552	.78544	.98358	1.12268	.78816	.93558	1.16388
.86179	1.11184	1.07513	1.24210	1.04563	1.07024	1.20817	.94763	.79687	1.07088

MIN F.S.= .66293 MAX F.S.= 1.51525



-----  
 FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES  
 -----

CLASS	INTERVAL	FREQUENCY										FRO	PCT
		0	10	20	30	40	50	60	70	80	90	100	
1	.66	.71	XXX										3 1.5
2	.71	.75	XXX										3 1.5
3	.75	.79	XXXXXXXXXX										9 4.5
4	.79	.83	XXXXXXXXXXXXXX										16 8.0
5	.83	.88	XXXXXXXXXXXXXX										16 8.0
6	.88	.92	XXXXXXXXXXXXXXXXXXXX										31 15.5
7	.92	.96	XXXXXXXXXXXXXX										17 8.5
8	.96	1.00	XXXXXXXXXXXXXX										16 8.0
9	1.00	1.05	XXXXXXXXXXXXXX										24 12.0
10	1.05	1.09	XXXXXXXXXXXXXX										23 11.5
11	1.09	1.13	XXXXXXXXXX										10 5.0
12	1.13	1.17	XXXXXXXXXX										10 5.0
13	1.17	1.22	XXXXXXXXXX										8 4.0
14	1.22	1.26	XXXXXX										6 3.0
15	1.26	1.30	XX										2 1.0
16	1.30	1.34	.										0 0.0
17	1.34	1.39	.										0 0.0
18	1.39	1.43	XX										2 1.0
19	1.43	1.47	XX										1 .5
20	1.47	1.52	X										1 .5

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 SAMPLE STATISTICS  
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MEAN = .952 S.D. = .148 SKEWNESS = .345 KURTOSIS = 3.62 SAMPLE SIZE = 200

-----  
 PROBABILITY OF SLIDING  
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P.F. = 54.88 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
 NORMAL WITH MEAN = .952 AND STD. DEV. = .148  
 P.F. = 95.98 % BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
 \*\*\*NUMBER OF SUCH CASES WERE 0

1234567890RS 040177 3-0 WEDGE EXAMPLE ANALYSIS

DIP DIRECTIONS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	320.00	9.07	270.00	50.00	287.22
PLANE B		50.00	90.00	320.00	73.77
TENSION CRACK T			0.00	90.00	
UPPER SLOPE S				-0.00	90.00
SLOPE FACE F					0.00

DIPS OF LINES OF INTERSECTION

	A	B	T	S	F
PLANE A	44.06	32.37	31.88	0.00	39.13
PLANE B		40.00	32.73	0.00	37.52
TENSION CRACK T			90.00	0.00	
UPPER SLOPE S				-0.00	0.00
SLOPE FACE F					70.00

ANGLES BETWEEN LINES OF INTERSECTION

PLANES	LINE	4	5	7	8	9
A S	3	90.0	50.4	130.6		
B S	4		56.4		122.7	130.0
A B	5			80.2	66.3	
A T	7					148.1
B T	8					32.7
S T	9					

PLANES	LINE	3	4	5
A F	1	114.8		64.5
B F	2		108.6	52.2

PLANE A HAS COHESION 2500. AND FRICTION ANGLE 25.0  
 PLANE B HAS COHESION 1000. AND FRICTION ANGLE 32.0

ASSUMED ROCK DENSITY IS 160.00 WATER DENSITY 62.40

WEDGE HEIGHT	WEDGE DEPTH	WEDGE WEIGHT	WEDGE VOLUME
250.00	132.89	***** - 336.04 (XE06)	753.66 - 210.03 (XE04)

AREA PLANE A 83460.- 32585. AREA PLANE B 75760.- 29579. AREA PLANE T 29579.

COEFFICIENTS FOR DETERMINATION OF EFFECTIVE NORMAL REACTIONS

	DIRECTION A	DIRECTION B
FORCE W	.43	.53
FORCE V	-.44	-.17
FORCE T	0.00	0.00

CASE 4 - TENSION CRACK - WATER HEIGHT 137.

WEDGE DEPTH 133.  
 FACE DIP DIRECTION = 0.0 WEDGE HEIGHT = 250. FACTOR OF SAFETY = .857

## 1234567890RS 040177 3-D HEDGE EXAMPLE ANALYSIS

## RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
 TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	70.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SD1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
SD2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIW	ALPW	APP	ATTI	CA	OAF	CB	08F
AVG	90.00	0.00	250.00	80.00	2500.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
SD1	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
SD2	0.00	0.00	0.00	0.00	2500.00	0.00	1000.00	0.00
SD3	0.00	0.00	0.00	0.00	3000.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	DENR	DENH	T	PHIT	ALPT	PDASHI	PDASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
SD1	5.00	0.00	0.00	0.00	0.00	0.00	0.00
SD2	0.00	0.00	0.00	0.00	0.00	0.00	.10
SD3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST= 123

## SAMPLE VALUES FOR FACTOR OF SAFETY

.65457	.88072	.81292	1.08128	.87382	.81420	.82955	.85962	.91668	.63698
.94820	.97553	.87812	1.00464	1.01960	.94442	.93694	.85732	.73800	1.09800
.77710	.56863	.75105	.71284	.76429	.64752	.67820	.77256	.84097	.78902
.95716	.99683	.81214	.76393	.89840	1.32798	.98712	.77841	.63126	.96286
.75268	.80286	.89472	.71998	.76325	.86151	.78540	.67473	.91232	.80746
.81142	.69697	.67446	.75337	1.10233	1.00594	.89895	.89458	.81520	.89288
.72339	1.07484	.65886	.78361	.94700	.78126	.70740	.63908	.83071	.82426
1.04259	1.07500	.82399	.78555	.79555	.84227	.53175	.82004	.81737	.89455
.82453	.75832	.81531	.75047	.76255	.83903	.83196	1.05282	.68366	.70447
.78054	1.00138	.96110	.89578	.58398	.90453	.95526	.82946	.92867	.97188
.80780	.94037	.72802	.76968	.95708	.68202	1.16357	.85306	.99758	.65606
1.08052	.76048	.89064	1.15028	.69085	.81937	.68624	.73186	.77372	1.33553
.94645	.75818	1.00263	.95937	.66615	.75788	.98391	.93454	.76202	.73630
1.00029	.63988	1.05759	.83552	.76878	1.20511	.92762	.92422	.94657	.82487
.86790	.93431	.76788	1.10084	.78463	.99026	.93471	.78320	.82630	1.00133
.86314	.83568	.90659	.95012	.70661	.74145	1.04640	.80395	.72464	.56678
.88615	.82503	.79794	.80209	.67389	.79134	.72258	.83002	.81783	.83399
.84258	.75333	.74450	.71205	1.27877	.87538	.73192	.80884	.86448	1.02292
.91347	.72435	1.39108	.98571	.70551	.81361	1.00151	.65687	.80843	.98820
.67030	1.00188	.97244	1.15132	.94455	.98721	.99238	.84982	.62456	.95695

MIN F.S.= .53175 MAX F.S.= 1.39108

```

PROBABILITY OF SLITTING
P.F. = 84.10 % BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS
NORMAL WITH MEAN = .655 AND STD. DEV. = .145
P.F. = 85.58 % 95 COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE
**NUMBER OF SUCH CASES WERE 0

```

WEDGE DEPTH = 154.  
FACE DIP DIRECTION = 0.0 WEDGE HEIGHT = 250. FACTOR OF SAFETY = .778

## 1234567890RS 040177 3-D HEOGE EXAMPLE ANALYSIS

RANGE AND TYPE OF DISTRIBUTION USED

TYPE 1 = GAUSSIAN, TYPE 2 = TRIANGULAR, TYPE 3 = UNIFORM, TYPE 4 = CUTOFF GAUSSIAN, TYPE 5 = EXPONENTIAL  
TYPE 6 = HISTOGRAM, TYPE 0 = NO SAMPLING PERFORMED

VARIABLE	PHIA	ALPA	PHIB	ALPB	PHIF	ALPF	PHIS	ALPS
AVG	44.06	320.00	40.00	50.00	80.00	0.00	-0.00	-0.00
TYPE	6.	1.	1.	1.	0.	0.	0.	0.
SC1	40.00	7.00	4.00	7.00	0.00	0.00	0.00	0.00
S02	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
I V	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
S A	.12	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
T L	.35	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
O U	.32	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
G E	.11	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
R S	.03	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
A	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
M	.02	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

VARIABLE	PHIW	ALPW	APP	ATTI	CA	OAF	CB	ORF
AVG	90.00	0.00	250.00	80.00	250.00	25.00	1000.00	32.00
TYPE	0.	0.	0.	0.	4.	1.	4.	1.
S01	0.00	0.00	0.00	0.00	500.00	2.00	700.00	2.00
S02	0.00	0.00	0.00	0.00	250.00	0.00	1000.00	0.00
S03	0.00	0.00	0.00	0.00	300.00	0.00	4200.00	0.00
H	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
I V	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
S A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
T L	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
O U	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
G E	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
R S	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
A	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00
M	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00

VARIABLE	OENR	OENW	T	PHIT	ALPT	PDASHI	PDASHK
AVG	160.00	62.40	0.00	0.00	0.00	0.00	1.00
TYPE	1.	0.	0.	0.	0.	0.	2.
S01	5.00	0.00	0.00	0.00	0.00	0.00	0.00
S02	0.00	0.00	0.00	0.00	0.00	0.00	.10
S03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
I V	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
S A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
T L	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
O U	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
G E	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
R S	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
A	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00
M	-0.00	0.00	0.00	0.00	0.00	0.00	-0.00

MFIRST=

123

## SAMPLE VALUES FOR FACTOR OF SAFETY

.57688	.79353	.75470	1.00419	.80250	.72578	.70904	.79276	.84410	.56435
.88788	.90033	.76252	.92044	.89563	.85800	.84687	.73824	.67819	1.00099
.70572	.49445	.68311	.63543	.67872	.52817	.59202	.69177	.78977	.73080
.88753	.87469	.72081	.68135	.80325	1.24695	.88397	.66961	.57136	.87550
.69642	.69816	.80591	.62319	.66616	.78300	.69830	.58230	.83413	.73169
.71755	.62742	.58219	.68515	1.04052	.92552	.81113	.81296	.74542	.80206
.65531	.95676	.59231	.70722	.85517	.70247	.63866	.54410	.72887	.70457
.95901	.97506	.73769	.70746	.71517	.75218	.45029	.70091	.73926	.83129
.77411	.65702	.75178	.67640	.67050	.74391	.71929	.92357	.60891	.61107
.69736	.91700	.89258	.80553	.49785	.82363	.85486	.71803	.84438	.88122
.72778	.86535	.64045	.70311	.85178	.60489	1.07069	.76910	.87664	.56467
1.01956	.69433	.76525	1.07330	.62750	.74469	.61674	.64826	.69462	1.27157
.85819	.67220	.90067	.87356	.58728	.68810	.86047	.85270	.64722	.66077
.90204	.58172	.99004	.73334	.69042	1.14020	.81361	.83321	.85986	.72916
.77032	.86057	.68975	1.02768	.70491	.93139	.86662	.70867	.74293	.91484
.80352	.72401	.83827	.85973	.63358	.67087	.97349	.71043	.64185	.50385
.80101	.72407	.66245	.74222	.60365	.70998	.63357	.77704	.73263	.72904
.71938	.66196	.63330	.65511	1.18928	.79763	.65156	.70900	.73946	.93208
.83636	.62931	1.29900	.87484	.64982	.74987	.91649	.57186	.72326	.87347
.55769	.92364	.89780	1.08336	.87380	.92639	.85676	.78108	.51909	.87774

MIN F.S.=

.45029

MAX F.S.=

1.29900

SIMPLE STATISTICS

MEAN= .770    S.D.= .145    SKEWNESS= .662    KURTOSIS= 4.29    SAMPLE SIZE= 280

### PROBABILITY OF SLIDING

P.F. = 94.44 X BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS  
NORMAL WITH MEAN = .770 AND STD. DEV. = .145  
P.F. = 93.50 X 9Y COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE  
\*\*\*NUMBER OF SUCH CASES WERE 0

FACTOR OF SAFETY	PHIF	0.0	0.5	1.0	1.5	2.0	2.5	3.0
*****	30.00	I.....+	.....I	.....+	.....I	.....+	.....I	.....I
		.	.	.	.	.	.	.
		.	.	.	.	.	.	.
1.925	40.00	I.....	.....	.....	.....*	.....	.....	I.....
		.	.	.	.	.	.	.
		.	.	.	.	.	.	.
1.192	50.00	I.....	.....	.....*	.....	.....	.....	I.....
		.	.	.	.	.	.	.
		.	.	.	.	.	.	.
.973	60.00	I.....	.....	.....*	.....	.....	.....	I.....
		.	.	.	.	.	.	.
		.	.	.	.	.	.	.
.857	70.00	I.....	.....	.....*	.....	.....	.....	I.....
		.	.	.	.	.	.	.
		.	.	.	.	.	.	.
.778	80.00	I.....+	.....*	.....I	.....+	.....I	.....+	I.....
		.	.	.	.	.	.	.

...PROBABILITY OF SLIDING AS A FUNCTION OF PARAMETER  $\Phi$ IF[illegible]

## REFERENCES

- C-1. "The stability of a rock slope containing a wedge resting on two intersecting discontinuities"; Quarterly Journal of Engineering Geology, v. 6, no. 1, pp 1-55; 1973.
- C-2. "Approximations for digital computers"; Princeton University Press, Princeton, N.J.; 1955.
- C-3. Powell, M.J.D. "An efficient method for finding the minimum of several variables without calculating derivatives"; The Computer Journal; v. 7, no. 2, pp 155-162; 1964.
- C-4. Beals, E. "MINSER an unpublished computer program"; Lawrence Radiation Laboratory, Berkeley.

## APPENDIX D

### PROGRAM DOCUMENTATION OF GENSAM

(general slip surface analysis including Monte Carlo simulation)





## ABSTRACT

The program GENSAM is a slices method of slope stability analysis employing circular and noncircular shear surfaces. Both total stress and effective stress analyses may be performed. For total stress analyses the option of specifying anisotropic variations in saturated undrained strength where  $\phi = 0$ , is available. For effective stress analyses, pore water pressures may be specified as a constant value within each strata, as a constant or variable function of total overburden pressure, as a series of values defined at arbitrarily selected points from which appropriate values are automatically selected by interpolation, as a piezometric surface, or as any combination of these. Complex slope geometries, includ-

ing left and right facing slopes with arbitrary surface pressure loadings, may be considered. The iterative procedure used to calculate the factor of safety completely satisfies static equilibrium. It employs the assumption of parallel inter-slice forces introduced by E. Spencer, and the extension to cases of noncircular shear surfaces and arbitrary external loads by S.G. Wright. An automatic search option is available for determining the circular shear surface with the minimum factor of safety. A Monte Carlo overlay option permits determination of slope reliability for specific input parameter distributions. Pseudo-static analyses for the study of earthquake effects cannot be performed.

## PROGRAM IDENTIFICATION

Program Title: General Slope Stability Analysis by the Spencer-Wright Procedure

Program Code Name: GENSAM (GENERAL SLIP SURFACE ANALYSIS INCLUDING MONTE CARLO SIMULATION)

Writer: Original Program - Stephen G. Wright (University of Texas);  
Monte Carlo Overlay - Hyung-Sik Kim and Geri Segal,  
Dames & Moore

Organization: Dames & Moore

Date of Documentation: March 1976

Updates: Monte Carlo Overlay added to program February, 1976

Source Language: Fortran IV

Availability: Mining Research Laboratories, Canada  
Centre for Mineral and Energy Technology, Department  
of Energy, Mines and Resources, 555 Booth Street,  
Ottawa, Canada, K1A 0G1.

Disclaimer: Neither the authors nor the Mining Research Laboratories can accept any responsibility for the accuracy of results produced by this computer program.

## PROGRAM DOCUMENTATION

### NARRATIVE DESCRIPTION

1. Program GENSAM can analyze the stability of a slope for any given shape of a potential sliding surface. Analysis is made by a method of slices, in which the potential sliding mass is divided into a number of vertical slices, and the equilibrium of each slice is considered. All conditions of equilibrium are satisfied.

2. The procedure includes the assumption that the inter-slice forces are parallel, an assumption first introduced by Spencer for a circular sliding surface. This was later extended to noncircular surfaces and arbitrary external loads by Wright. The solution for the factor of safety is obtained by iteration and requires successive approximations for the factor of safety and side force inclinations to satisfy the equilibrium boundary conditions (D-1 and D-2).

3. The initial program development and documentation by Wright was intended for use in the analysis of slopes in soils. It therefore includes many options, such as anisotropic shear strengths and the manner in which the water pressure distribution is specified, which will probably not be used in applying the program to rock slope stability. As mining companies may also find this program useful in the analysis of

tailings dams, waste embankments, and foundations, all original options have been retained.

4. The option of performing probability analyses is by Monte Carlo overlay, which has been documented separately.

### METHOD OF SOLUTION

5. This section consists of two parts. In the first, the formulation and solution of the deterministic method of slope stability analysis by Spencer and Wright is summarized. This analysis is the essential basis for the probability analysis described in the second part.

#### Deterministic Analysis

6. Since details of the method of solution are given in the references cited only a general description is presented here.

7. The program performs a two-dimensional slope stability analysis by a limit equilibrium method using the factor of safety concept. The distinguishing feature is the inclusion of moment equilibrium in the formulation.

8. Consider one of the vertical slices into which the sliding mass is divided for the purpose of analysis, Fig D-1. It is assumed that the shear force,  $S_m$ , mobilized along the surface, ie,

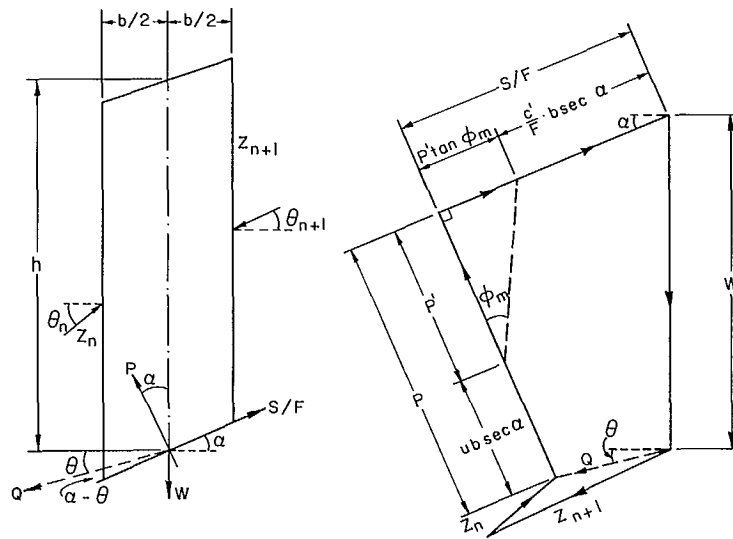


Fig D-1 - Forces acting on a typical slice.

the base of the slice, is a fraction of the available shear strength along this surface. This is expressed as follows:

$$S_m = \frac{S}{F}$$

where  $F$  is the factor of safety and is to be determined.

9. The normal force acting on the base of the slice,  $P$ , is determined from the normal component of the weight of the slice. The location of this force is unknown.

10. Integrating the stresses along the vertical side of the slice gives a resultant side force of unknown magnitude,  $Z$ , oriented in an unknown direction,  $\theta$ , with an unknown point of application.

11. As every slice is in both force and moment equilibrium, the vectorial sum of both forces and moments for each slice must be zero. Since the entire mass is in equilibrium, the sum of all forces and moments external to the mass must also vanish. The sum of all forces due to forces internal to the mass, ie, due to inter-slice forces, must also equal zero.

12. These conditions yield fewer equations than there are unknowns. It is therefore necessary to make assumptions to obtain solutions to the equations. The assumptions made, which are the

unique part of the Spencer-Wright solution, are as follows:

- all inter-slice forces are parallel;
- for each slice, the weight, the normal force on the base of the slice and the resultant of the two side forces are coincident at the mid-point of the base of the slice.

13. With these assumptions, the force and moment equilibrium conditions generally provide a system of equations from which the factor of safety,  $F$ , the side force inclination,  $\theta$ , and the side force magnitude,  $Z$ , can be found by a suitable numerical technique. In GENSAM, the Newton-Raphson method is used to solve for  $F$  and  $\theta$ .

14. It should be noted that these assumptions, while generally satisfactory, can result in difficulties in obtaining a solution in certain circumstances. Consider, for example, the slope shown schematically in Fig D-2. To simulate liquefaction of the layer through which the horizontal shear surface is drawn, zero shear strength may be assigned along the horizontal line.

15. The assumptions of the Spencer-Wright procedure imply that the tangential forces along the horizontal shear surface of each slice are zero. Hence, the sum of the side forces acting on each slice,  $Q$ , is also zero or vertical. This is not

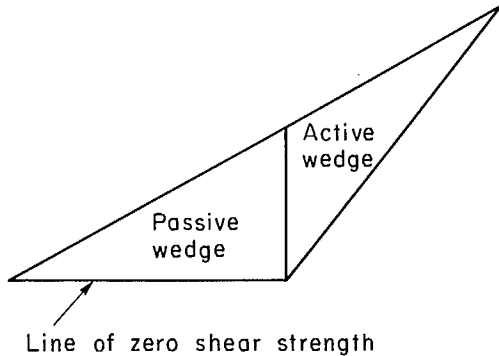


Fig D-2 - Invalid zero shear strength assumption.

the case for the slices of the active wedge. The assumption of parallel interslice forces is thus invalidated, and the iterations for  $\theta$  and  $F$  will not converge because either force equilibrium or moment equilibrium, but not both, can be satisfied.

16. The difficulty is not overcome automatically by GENSAM, and so a slope such as the one above cannot be analyzed routinely by the program. There are, however, ways of considering the problem. For example, realizing that the factor of safety along the horizontal shear surface is an ill-determined quantity, the active wedge of the slope could be considered alone. Alternatively, the problem could be analyzed satisfying only force equilibrium but not moment equilibrium. This is not performed automatically by the program, but can be done by varying  $F$  and  $\theta$  manually by trial and error until an acceptably small force imbalance results.

#### Probabilistic Analysis

17. The factor of safety was introduced into the formulation of the above analysis. In this way, it is a measure of mobilized shear strength along the slide surface. To be rigorous, it should be different for each segment of the surface. For simplicity, the common assumption of a constant factor of safety for each segment is, however, made.

18. A slope is considered critical if  $F$  has a value less than a critical value,  $F_c$ . The critical value is usually taken to be unity, which indicates a state of limiting equilibrium.

19. The object is to identify the shear surface with the minimum factor of safety for a given slope configuration and soil properties. If the minimum value is less than the critical factor of safety,  $F_c$ , the slope is regarded as unsafe.

20. It is realized that this can be done only in a probability sense, since the factor of safety,  $F$ , can be ascertained only with some degree of uncertainty. In other words, it cannot be definitely stated that a given slope will be either stable or unstable, only that the slope has a probability of being unstable or conversely, that the slope is stable, with some stated reliability.

21. The reason for this is attributed to the inherent uncertainties associated with the variables on which the factor of safety depends. The variables may be material properties. They may also be those variables describing the geometry of the soil profiles, the piezometric line, and others that are required in the deterministic analysis.

22. If the uncertainties associated with these program input variables can be specified, the variation of the factor of safety about its mean can be determined. In turn, this means that the probability of sliding along a given surface can be calculated.

23. The method used in this program to determine slope reliability is by Monte Carlo sampling. The details are described separately in Appendix E. Briefly, the computer is used to sample values from input stochastic variables. The corresponding value of the factor of safety is then computed, using the deterministic method described previously. If this process is repeated NSAMPL times, NSAMPL values of  $F$  are obtained. If the sampling is random, then the obtained sample distribution of  $F$  is random, and standard statistical methods can be applied to determine the probability that  $F$  will be less than  $F_c$ .

24. The requirements for specifying the uncertainties of the input variables are described in the section on Probability Analysis Input.

#### PROGRAM CAPABILITIES

25. The program can be used for analyzing circular or non-circular sliding surfaces with various options for handling pore water pressures, surface pressures, and various combinations of soil strength parameters, including variation of strength parameters in an individual stratum and along the potential sliding surface. Right and left facing slopes can be analyzed. Tension cracks and the water in them can be taken into account. The program can also be used to analyze bearing capacity problems.

26. The program has an option for searching for the critical circular sliding surface associated with the minimum factor of safety. The Monte Carlo overlay option enables the reliability of a slope to be determined.

27. The program has the following limitations.

- a. Vertical soil profile line segments may not be used.
- b. The origin of the coordinate system should be located in the vicinity of the slope, ie, within a maximum distance of ten times the slope height.
- c. Pseudo-static analysis to include the effect of earthquake forces cannot be performed.
- d. The maximum number of soil profiles allowed is 20.
- e. The maximum number of material types is 20.
- f. The maximum number of points on each profile line is 15.
- g. No variation in unit weight of material with depth is permitted within a stratum.
- h. Water in the tension crack gives rise to a horizontal force, and the effect of pore water pressure in the crack is not included.
- i. The method is not very amenable to hand computation for checking purposes, compared with other methods of slope stability analysis.
- j. During the iteration procedure, the side force inclination is not permitted to change by more than  $10^\circ$ . In addition, the side force is not permitted to reach an inclination steeper than  $85^\circ$ ; if this limit is reached, the solution will fail to converge. Either a negative side force inclination for a right facing slope, or a positive side force inclination for a left facing slope will prevent convergence.
- k. The specified values for the maximum allowed force and moment imbalances correspond essentially to the maximum permissible error in static equilibrium. Experience with the program has shown that for most typical slopes, the values of the factor of safety and side force inclination are both accurate to within four significant figures, 0.01%, when the allowed force and moment imbalance are 100 lb and 100 lb-ft, respectively (D-3). The user is, however, expected to verify the accuracy of his results for the specified limits used. The values of these limits may not be specified as zero, because round-off error and computer tolerance normally preclude computation of an exact zero value for verifying convergence.
- l. When reasonable values are assumed for the factor of safety and side force inclination, convergence to a solution is normally attained within 3 to 10 iterations. This assumes that the factor of safety is estimated to within the correct value by approximately 1.5, and the side force inclination is estimated within  $20^\circ$  of the correct value.  
If the solution fails to converge within an apparently reasonable number of iterations, the user should examine the step-by-step iteration data. When this problem is encountered during an automatic search, the user must specify individual shear surfaces separately to obtain the step-by-step iteration data. In an automatic search this information is usually given only for the final critical circle.
- m. The method of analysis assumes that the resultant of the side force inclination  $\theta$  is the same for every slice.
- n. The sliding mass may be divided into a maximum of 99 slices. If input data requires more than

99, the data are adjusted so that only 99 are required.

- o. Array size limitations when using the probability analysis are given below.

#### Advantages of the Spencer-Wright Program

- a. The shear surface intersection with the slope lines can be vertical or near vertical. This feature is difficult to handle in the computer solution based on Bishop's method without introducing instability (D-3).
- b. Non-circular shear surfaces can be analyzed with this program. Other methods can also handle irregular shear surfaces. They need more computation time and require judgment and trials in determining the side force function on the sides of the slices.
- c. The method satisfies all conditions of equilibrium and is numerically the most stable at the present time (D-3). Since it satisfies all conditions of equilibrium, the possible inaccuracy in the factor of safety is very small.
- d. The program has various error messages to help the user recognize incorrect input data.
- e. The computer program is so written that profile lines and the material property data are independent inputs. Consequently, profile data and material property data can each be altered without affecting the other.
- f. The trial circles may be used for either right or left facing slopes.
- g. The program can account for the effect of a vertical tension crack containing water extending from the ground surface to the shear surface.

#### INPUT

28. The description of input data is presented in two parts. The first part is a general explanation. The second part is presented in Exhibit D-1. In this exhibit each individual data card is described, and the formats for coding the input data are specified.

#### Coordinate System

29. The surface profile and slope geometry

data are specified in terms of the x and y-coordinates in a righthand coordinate system, the x axis being horizontal and positive to the right, the y axis being vertical and positive in the upward direction. The origin of the coordinate system may be arbitrarily located; the origin should, however, be located in the vicinity of the slope, within a maximum distance of ten times the slope height. No restrictions are placed on the sign of the coordinate values, and both positive and negative values may be used in the same problem.

#### Data Units

30. The input data should be in consistent units, such as feet and pounds. If necessary, other units may be used provided they are consistent; the computer printout will, however, be labelled in units of feet and pounds.

#### Definition of Terms

31. The following terms are used in the description of this computer program,

- a. Soil profile refers to the cross-sectional representation of all material to be considered in the analysis. The profile may consist of several soil types and may also include other materials such as rock, concrete, and timber.
- b. Soil stratum refers to a particular layer or mass of soil within the profile.
- c. Profile lines are the lines used in series to define the geometry of the soil profile. Profile lines are used to define the boundaries between soil strata and variations in strength within soil strata.

#### Profile Lines

32. Two types of profile line may be used to define the properties of the soil strata.

33. Type I: The soil beneath the profile line, down to the depth of the next profile line is assigned the properties corresponding to a particular material type. The strata beneath the lowest profile lines are assumed to extend to infinite depth.

34. Type II: This type of profile line represents a line of constant shear strength, the

strength at points between lines being determined by linear interpolation in the vertical direction. At least two such lines must be used to describe strength variations within a single soil stratum.

35. Profile lines are defined in the data input by specifying x and y-coordinates along the profile line from left to right. A profile line is continuous, but is not necessarily straight, and may be composed of several shorter straight-line segments connecting the specified x and y-coordinates. Vertical profile line segments may not be used. The "number of profile lines" refers to the number of continuous profile lines and not to the total number of shorter straight-line segments which make up each profile line. The order in which the profile lines are specified is immaterial, and Type I and Type II profile lines may both be used to define the soil profile for the same problem. The profile line type, ie, I or II, is not specified with the profile line data but rather with the associated material property data.

36. When Type II profile lines are used to specify the strength variation within a soil stratum, they must be specified at both the upper and lower boundaries of the stratum. Others may be used at intermediate levels to describe complex strength variations. Thus, a minimum of two Type II profile lines are used. If a soil stratum for which these profile lines are used overlies a second stratum, the profile line between the two strata must be defined twice in the data input, once for the bottom of the upper stratum and once for the top of the lower stratum.

37. All Type II profile lines are identified by means of a code, KI. This code is specified with the material data for each and provides the means for identifying all Type II profile lines which lie within a particular soil stratum, the value of KI being identical for all profile lines within each stratum. Type II profile lines in other strata are assigned different values of KI, and if used to define two strata which are vertically adjacent, the value of KI for the lower stratum must be greater than the value of KI for the overlying stratum.

#### Material Data

38. Each profile line has associated with it a particular material type, MATYPE, and several profile lines may have the same material type. Material data may be specified in a number of ways. The shear strength of the soil is described in terms of the Mohr-Coulomb strength criterion,

$$s = c + (\sigma - u) \tan \phi$$

where

c = the cohesion of the soil,

$\phi$  = the angle of internal friction of the soil,

$\sigma$  = the total normal stress on the assumed shear surface and

u = the pore water pressure on the assumed shear surface.

39. The values of c,  $\phi$ ,  $\sigma$ , and u used for each slice are taken to be at the midpoint of the base of the slice. If the strength of a particular stratum is expressed in terms of total stress, the values of c and  $\phi$  are total stress strength parameters, and the pore water pressure is specified as zero within the stratum. For effective stress analyses, c and  $\phi$  are the effective stress parameters, and an appropriate representation of pore water pressure is specified. Saturated undrained ( $\phi = 0$ ) shear strengths are specified only in terms of c.

40. The manner in which the strength information is specified depends on the type of profile line with which the material data are associated, ie, Type I or Type II, as follows:

#### Type I Profile Lines

41. The shear strength of a material may be specified in terms of:

- the total or effective stress strength parameters, ie, c and  $\phi$ , or c' and  $\phi'$ , and
- the value of the saturated undrained shear strength, c, with  $\phi = 0$ ; in this case the values of the undrained shear strength may:
  - vary with depth within the stratum,
  - vary with orientation of the sliding plane or

shear surface, taking anisotropy into account,

vary with both depth and orientation of the sliding plane.

42. Strength variations with depth are specified in terms of a value of the undrained shear strength,  $c$ , at an arbitrarily selected reference elevation, REFHT, and the increase or decrease in undrained shear strength, CUPONZ, with depth below the reference elevation. If strengths increase with depth below the reference elevation, they are

assumed to decrease at an identical rate above the reference elevation.

43. Variations in strength with sliding plane orientation are specified in terms of the value of the saturated undrained shear strength for specific orientations. Referring to Fig D-3, the strength values would be specified for  $10^\circ$  increments in orientation of the sliding plane from  $-90^\circ$  to  $+90^\circ$  inclusive. This requires 19 separate data cards. It may be noted from Fig D-3 that a  $-90^\circ$  sliding plane orientation would

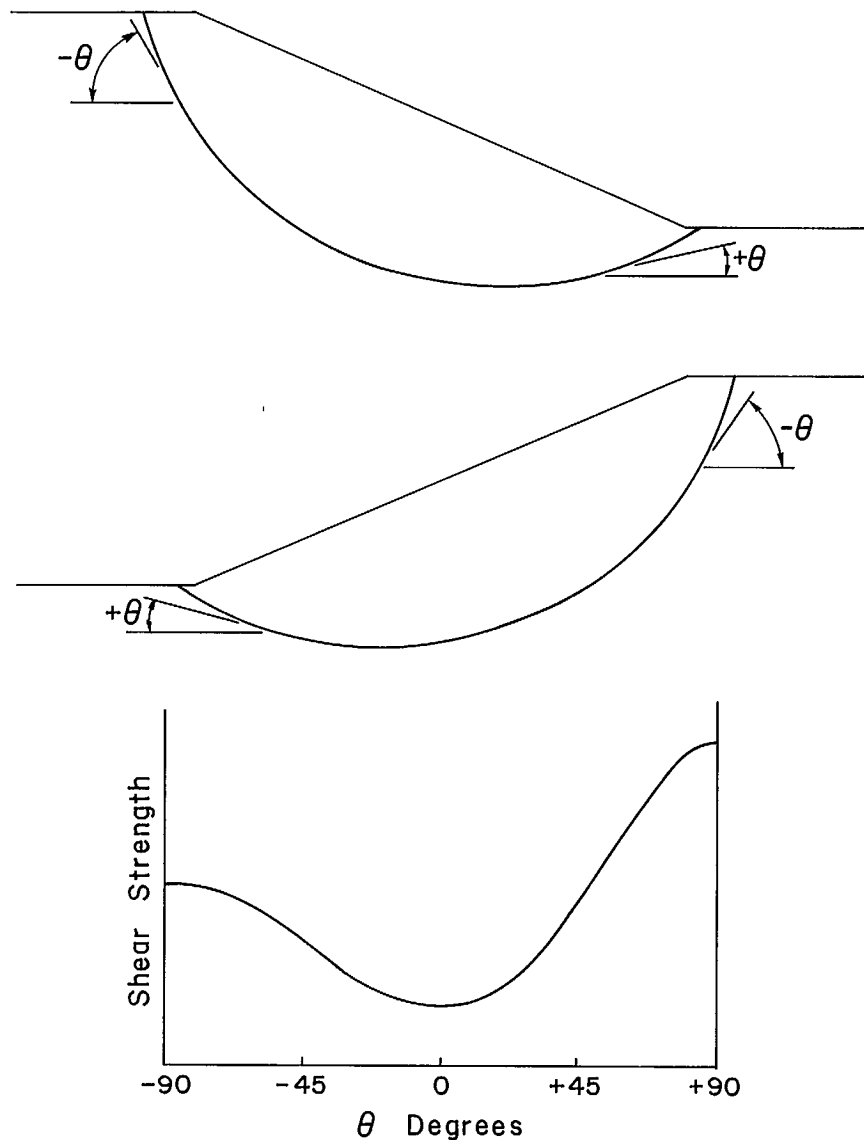


Fig D-3 - Sign convention for sliding surface; orientation used with anisotropic shear strengths.



correspond to a vertical sliding plane near the crest of the slope, while a +90° orientation would correspond to a vertical sliding plane near the toe of the shear surface.

44. The value of the code KEY on the material data cards is used to identify the type of profile line, Type I or Type II, with which the material data are associated. The value of KEY is equal to zero for all materials for Type I profile lines, unless anisotropic variations in undrained shear strength are used, in which case KEY must be equal to 1, and 19 strength data cards must be input for the material.

45. If the undrained strength varies with depth and sliding plane orientation, 19 data cards are used to specify the strength values at the selected reference elevation, REFHT, and the increase in strengths below the reference elevation, each data card corresponding to a specific sliding plane orientation, as described. The reference elevation for strength variations with depth is the same for all sliding plane orientations and is specified on only the first of the 19 data cards.

#### Type II Profile Lines

46. The shear strength for Type II profile lines is specified in terms of the value of the saturated undrained strength,  $c$ . This value of the undrained shear strength is the value on the profile line, and strength values at points between profile lines are obtained by linear interpolation in the vertical direction. Anisotropic variations in shear strength may not be specified for Type II profile lines. The values of KEY must be equal to 2 for Type II profile lines, and the code KI must have a positive, non-zero value.

#### Unit Weight of the Soil

47. For both Type I and Type II profile lines, the unit weight of the soil beneath the profile line and down to the depth of the nearest underlying line, is assumed to be constant. No provisions are made for variation in unit weights between profile lines.

#### Pore Water Pressure Data

48. Pore water pressures with a soil stratum

may be specified in one of several ways and may be defined in a different manner for each individual stratum. The way in which pore water pressure is represented is determined by the value of an input code, KODEP. This code is specified on the material data cards and is interpreted as follows:

- a. KODEP = 0: the pore pressures are zero or no pore pressures are specified.
- b. KODEP = 1: the pore pressures are defined in terms of a constant value of the pore pressure coefficient  $r_u$  ( $=u/\gamma h$ ), where  $r_u$  is the ratio of pore water pressure to vertical soil overburden pressure.
- c. KODEP = 2: the pore pressures are specified as a constant value throughout the material.
- d. KODEP = 3: the pore pressures are interpolated from values of the pore pressure, which are specified at selected coordinates within the soil stratum.
- e. KODEP = 4: the pore pressures are defined in terms of the pore pressure coefficient,  $r_u$ , and its value is obtained by interpolation from values of  $r_u$  specified at selected coordinates within the soil stratum.
- f. KODEP = 5: the pore pressures are determined from the piezometric line which is specified as input data.

49. When the value of KODEP is less than 3, all necessary pressure data can be specified on the material data cards. If KODEP has a value of 3, 4, or 5, additional data cards are, however, required as described in the following section.

#### Pressure Data

50. The pressure data include the information for the values of pore pressure and  $r_u$  when the value of KODEP is equal to 3 or 4, and the information for the piezometric line when the value of KODEP is equal to 5. This data format also includes the data for pressures acting on the surface of the slope. All of the above data cards include an identification code, MTYPE, which indicates the manner in which the data are to be used.

For internal pore water pressure and  $r_u$  data, the value of MTYPE must be equal to the material type to which the data of one of the input data codes, MBPL1 or MBPL2, which are described below. For piezometric line data, MTYPE must be equal to the value of an input data code, NPIEZ.

51. A description of the pore water pressure,  $r_u$ , surface pressure, and piezometric line data is given below; though all such data are referred to as "pressure data", it should be noted that the form of input and interpretation are different for each case.

#### Pore Water Pressure Data

52. When the value of KODEP is equal to 3 or 4, pore water pressures or values of  $r_u$  are interpolated from specified values of pore pressure, or  $r_u$ , and their corresponding x and y-coordinates. In general, the specified coordinates may be arbitrarily located and are not restricted to a square, rectangular, or uniformly spaced grid system. The procedure for interpolation used in the computer program is as follows

53. Step 1: The six points closest to the one under consideration, and in the same material, are selected.

54. Step 2: The four points closest to the interpolation point are used to evaluate the four coefficients,  $a_j$ , in the following interpolation formula:

$$u \text{ or } r_u = a_1 + a_2X + a_3Y + a_4XY$$

This is then used to determine the value of u or  $r_u$  at the base centre of the appropriate slice.

55. Step 3: If the coefficients  $a_j$  are indeterminate the most distant of the four points used in Step 2 is replaced by the next closest point located in Step 1, and Step 2 is repeated. The coefficients are indeterminate if the determinate of the coefficient matrix used in solving for the values of  $a_j$  is zero, which may occur if three or more points lie in a straight line. It also occurs if two points lie on a line parallel to the x-axis and the other two lie on a line parallel to the y-axis, noting that the interpolation formula used is not invariant to

direction of co-ordinates.

56. Step 4: If the coefficients,  $a_j$ , are still indeterminate, the most distant of the four points last used is replaced by the sixth point located in Step 1, and Step 2 is repeated again.

57. Step 5: If the coefficients,  $a_j$ , in the interpolation formula cannot be evaluated in three attempts, a three point interpolation of the following form is used:

$$u \text{ or } r_u = b_1 + b_2X + b_3Y$$

The coefficients,  $b_j$ , are evaluated using the three points closest to the centre of the base of a slice. The formula is then used to solve for the desired value of u or  $r_u$ .

58. Step 6: If the coefficients,  $b_j$ , cannot be evaluated using the three closest points, the most distant of the three is replaced by successively further points as located in Step 1, until the coefficients can be evaluated or the six points have all been used.

59. Step 7: If none of the above steps results in a successful evaluation of the required coefficients,  $a_j$  or  $b_j$ , the particular trial shear surface is abandoned.

60. At least six values of pore water pressure or  $r_u$  must be specified for each material in which the interpolation option is to be used. Care should be exercised in specifying pore pressure or  $r_u$  values for interpolation, to ensure that the five points closest to any other point are not along a single straight line. For example, if pore pressures are specified at closely spaced intervals along straight lines at the top and bottom of a relatively thick stratum, there may be difficulties in interpolating values in that region.

61. Care must also be taken not to specify values for pressure interpolation at points which encompass only a portion of the total region comprising the stratum. Extrapolation of pore pressures to points considerably beyond the region in which pressures are specified may lead to significant errors. For this reason it is suggested either that several points of zero pressure be specified within areas of the soil

stratum where the pore water pressure is zero, or that the stratum be divided into two layers, one with positive pore pressures and the second with zero pore pressure. The latter alternative is preferable.

#### Surface Pressure Loadings

62. Pressures acting normal to the surface of the slope, or ground surface, are specified in terms of the values of the pressure at selected points, proceeding from left to right. All coordinates of pressure points must be coincident with the slope lines, and the pressure must be specified at all breaks in the slope profile. Surface pressure may not be specified for a vertical slope. The value of the pressure at any point on the slope is determined by linear interpolation between points at which the pressures are specified. The values of the surface pressure to the left of the first point specified and to the right of the last point specified are assumed to be zero.

63. The value of the code, MTYPE, which is specified for each surface pressure data point, must be equal to the value of one of the input parameters MBPL1 or MBPL2; which of these two values is used depends on the distribution of the surface pressures. All surface pressure data, up to and including the point of the first discontinuity in pressures, must have a value of MTYPE equal to the value of MBPL1. If surface pressures are specified beyond the first point of discontinuity, the value of MTYPE for these additional points, beginning with the first point at which additional pressures are specified, must be equal to the value of MBPL2.

64. If there is more than one discontinuity the values of the code, MTYPE, must alternate between the values of MBPL1 and MBPL2 at each discontinuity in pressures from left to right. At any point on the surface for which the nearest pressure values to the left and right do not have the same value of the code, MTYPE, the surface pressures are assumed to be zero.

65. Figure D-4 illustrates the appropriate use of the value of MBPL1 or MBPL2 for the code, MTYPE. It should be noted that the surface

pressures are assumed to act normal to the slope or ground surface. For example, if a load acts vertically the slope geometry must include a horizontal section where the pressures are applied.

#### Piezometric Line Data

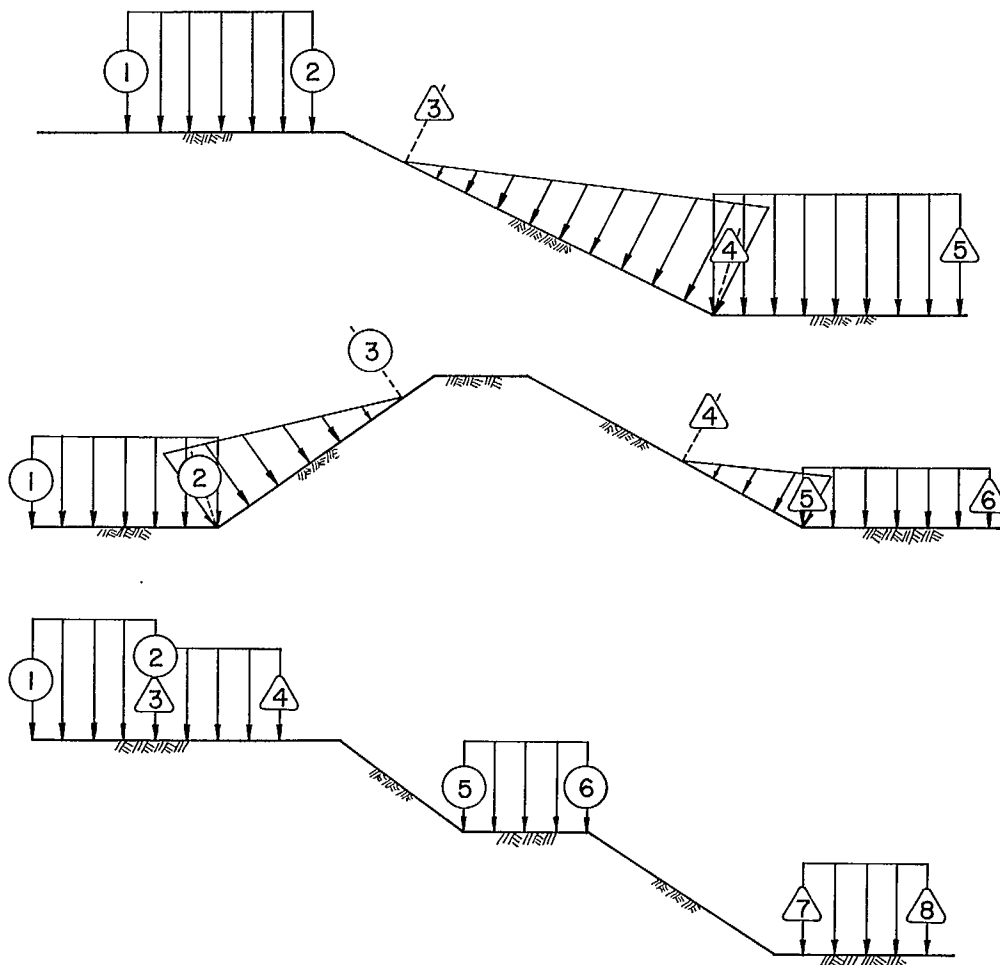
66. Data for the piezometric line are specified in terms of the x and y-coordinates of points along the line from left to right. These points are assumed to be connected by straight lines which define a single continuous piezometric surface, applicable to all materials which have pore water pressures defined in terms of the piezometric line. Separate piezometric lines cannot be specified for different strata; if two strata are, however, situated horizontally so that no vertical line intersects both a single continuous piezometric line may be used to indicate different piezometric elevations in the two strata.

67. When the pore water pressure on the base of a slice is determined from piezometric line data, the pressure is computed as the product of the vertical distance from the centre of the base of the slice to the piezometric line, multiplied by the unit weight of water, assumed to be 62.4 lb/cu ft, unless otherwise specified. If the base of the slice lies above the piezometric line the pore water pressures are assumed to be zero.

#### Slope Geometry

68. The slope geometry, including the ground surface to the left and right of the slope, is specified in terms of the x and y-coordinates of points, from left to right. All points are assumed to be connected by straight lines, and coordinate points should be defined at sufficient distances to the left and right of the slope to include the intersection point between any trial shear surface and the slope or ground surface. Although vertical profile lines may not be specified, vertical slopes may.

69. The slope may face either to the right or to the left, and if necessary both slopes of a full embankment section may be analyzed with the same slope geometry input data.



Numbers enclosed by circles and triangles indicate the sequence of specified surface pressure data at the required locations. A circular or triangular symbol indicates the corresponding value of the code, MTYPE, for each data point, as follows:

- MTYPE = MBPL1  
 △ MTYPE = MBPL2

Fig D-4 - Examples of surface pressure coding.

70. The program may be used to analyze several slope configurations in the same conditions. To do so, it is only necessary to specify new slope geometry data to be used with the same profile data, provided that profile lines have been specified to include all ground beneath each slope. When surface pressure loadings are employed, however, it may be necessary to repeat the profile data for each new slope geometry,

because the surface pressure data specified with the profile data, must correspond to each set of slope geometry analyzed.

#### Shear or Slip Surfaces

71. The type of shear surface used to compute the factor of safety and the option to search for a critical circular shear surface are indicated by the specified value of the input code ITYPS as

follows

- a. ITYPS = 1: a single, individually selected, circular shear surface is to be used.
- b. ITYPS = 2: a single, individually selected, non-circular shear surface is to be used.
- c. ITYPS = 3: the program is to search automatically for a critical circle.

72. Depending on the selected option, as indicated by the value of ITYPS, the data input will follow one of the forms described below.

#### Circular Shear Surface

73. The location of a selected trial circle is specified in terms of the coordinates of the centre of the circle and either the radius of the circle or the coordinates of a point on its assumed circumference.

74. The subdivision of the circle into slices is carried out in one of two ways, the one selected being specified in the input data

- a. The angle, THETA, subtended by radii extended to each side of the base of each slice is specified.
- b. The arc length, ARCMAX, along the base of each slice is specified.

75. A value of either THETA or ARCMAX is specified as input data. Depending on which of these two variables has a non-zero value, slice coordinates are generated along the circle by using one of the above two criteria. If the specified value of THETA or of ARCMAX results in more than the 99 slices allowed, the value will be successively doubled until a small enough number of slices results. The program may use smaller subtended angles and shorter arc lengths at locations where additional circle coordinates are required by the program.

76. Trial circles may be used for either the right or left face of a slope or embankment, and no restriction is placed on the direction in which the slope faces.

77. A vertical crack of selected depth DTC may also be specified with the circle data. The crack is assumed to be located at the point where the

sliding surface is at a vertical distance DTC from the slope face along the up-slope portion of the arc. Groundwater in the crack may also be considered by specifying the depth of water above the shear surface as the input variable DWATER. The water in the crack is considered as a horizontal force and is not considered to have any direct influence on the pore water pressures in the soil.

#### Non-Circular Shear Surface

78. The location of a non-circular shear surface is defined by specifying a selected number of coordinates from left to right along the surface. The specified coordinates are assumed to be connected by straight line segments; vertical segments may not be specified. Specific coordinates required in the program, eg, where the shear surface crosses a profile line, need not be specified as input data; those omitted are generated by the program itself. The number of slices is determined by the number of coordinates specified plus the number of required coordinates generated.

79. If the shear surface intersects a horizontal slope line, the coordinate at the end of the shear surface at that point should be specified to have precisely the same y-coordinate as the slope line, and if the shear surface intersects a vertical slope line, the coordinate at the end of the shear surface at that point should indicate the same x-coordinate as the slope line. It is virtually impossible to specify precisely the intersection of the shear surface with an inclined slope line, and provision is made in the program to correct the end point coordinates of the shear surface if they lie outside the slope. Care must be taken, however, to ensure that the last two coordinate points at either end of the shear surface are not both above the slope.

80. If a vertical crack is to be specified, the coordinates of the shear surface should be terminated along the up-slope portion of the shear surface at a point corresponding to the base of the crack. As described previously for circular shear surfaces, such a crack may also be specified

as being filled with water to a depth DWATER.

#### Search Procedure

81. The program may use the following three modes of search to locate the centre of a critical circle

- a. MODE 1: all circles are assumed to be tangent to a hypothetical horizontal line referred to as a "rock line".
- b. MODE 2: all circles are assumed to pass through a fixed point, commonly the toe of the slope.
- c. MODE 3: all circles are assumed to have a fixed radius which does not vary with the centre point location.

82. By varying successively these three modes of search, according to the sequence of steps outlined below, the program is capable of locating an overall critical circle corresponding to a minimum value for the factor of safety.

83. Step 1: the critical circle is located for an initial mode of search which is specified on input as either Mode 1 or Mode 2. For Mode 1, the y-coordinate elevation of the hypothetical rock line must be specified as input data. For Mode 2, the x and y-coordinates of the point through which the circles pass must be specified.

84. Step 2: when the critical circle is located for the initial mode of search, the mode of search is automatically changed. If the initial mode of search was Mode 2, the search is changed to Mode 1, and the new rock line elevation is defined as the elevation of the bottom of the critical circle located Mode 2. If Mode 1 is specified for the initial search, the mode is changed to Mode 3, and the radius used corresponds to that of the most critical circle found in the previous search mode. If the difference between the values for the factor of safety of the two critical circles located by the modes of Step 1 and Step 2 is less than 0.001, the critical circle is considered to be the most critical circle located in Step 2, and the search is completed. If this criterion is not satisfied, however, the search will continue to Step 3.

85. Step 3: After Step 2, the mode of search will alternate between Modes 1 and 3, until the

difference between the values of the factor of safety for successive modes is less than 0.001. Mode 2 will never be used beyond Step 1 and, therefore, may be used only for the initial mode of search.

86. When locating the overall critical circle it may be desirable to impose some limiting depth upon it. This may be done either by specifying a layer at the selected limiting depth and assigning a high shear strength to it, or by specifying a limiting y-elevation below which the critical circle is not allowed to pass. If the latter is chosen, the selected limiting y-elevation is specified in the data input for the search as the variable, ROCK. If no limiting depth is to be imposed the value of ROCK must be a very large negative number, which places the limiting depth far below the slope.

87. The program also includes the option of terminating the search after Step 1 is completed. In this case the input variable, ROCK, serves as a control parameter which must have a specified value of exactly 99 and has no meaning with respect to the limiting depth of the circle.

88. For each mode of search, the location of the centre of the critical circle is found by using a 3 by 3, square, 9-point grid. The spacing between grid points is reduced during the search, and the location of the centre point of the grid is shifted until it corresponds to the centre of a circle which has a lower value for the factor of safety than any of the eight other circles whose centres are located on the perimeter of the grid. The search is terminated when the grid spacing has been reduced to a specified accuracy, ACC. The initial size of the grid is 20 times ACC.

89. The centre point of the first grid used for the initial mode of search is specified in the data input as the best estimate of the x and y-coordinates of the centre of the critical circle. For all subsequent grids used during the remainder of the search, the centre of the grid is located at the grid point found to have the lowest value for the factor of safety.

90. Computed values for the factor of safety are stored by the program, and in most cases only those values which have not been previously

calculated are computed. In the printout the factor of safety for each circle is listed, and the data for each group of circles in a grid are separated by a line of asterisks, \*\*\*\*. It should be noted, however, that only those circles for which the factor of safety has not previously been computed will be listed for each grid; thus data may be given in some cases for as few as two circles per grid.

91. In some cases it may be possible to find several local critical circles with minimum factors of safety, each surrounded by grid points having higher values. The existence of such local minima depends on the profile being analyzed. If more than one local minimum exists, it is necessary to locate each of the several circles whose centres represent local minima. The corresponding values of the factor of safety for each of these circles must then be compared by the user, to determine the actual value of the minimum factor of safety and the location of the overall critical circle.

92. To facilitate locating the overall critical circle in cases where it appears that several local minima exist, the computer program permits several searches to be made for the same problem. The number of searches to be carried out is specified in the input data, and for each search, different estimates of the location of the critical circle, and initial modes of search, may be specified.

93. When the search option is used, the procedure used for subdividing the circle into slices is identical with the procedure described previously for individual circular shear surfaces.

#### Shear Surfaces for Bearing Capacity

94. Special precautions must be taken when shear surfaces are specified for bearing capacity analyses. This is necessary to ensure that the shear stresses act in the proper direction along the shear surface. When a horizontal slope and surface pressures are specified, instability is assumed to produce a counter-clockwise rotation, or a similar displacement pattern for non-circular shear surfaces, and the shear stresses developed by the mobilized shear strength are assumed to act

to the left. The instability mode is thus assumed to be similar to that for a slope facing to the right, and shear surfaces must be oriented in a manner consistent with this mode of instability.

95. For bearing capacity analyses on inclined surfaces, the instability mode and the direction of the shear stresses are assumed to be controlled by the gravity component of loading. If an inclined surface or slope is specified, the direction in which the shear stress acts is determined by comparing the elevations of the two coordinates at each end of the shear surface at its intersection with the slope. If the right coordinate is higher in elevation, ie, the y-coordinate value, than is the coordinate on the left, the slope is assumed to face to the left, and the shear stress is assumed to act to the right along the shear surface. Otherwise, it is assumed that the shear stress acts to the left and the slope faces to the right. Because of this procedure, some analyses should not be attempted with the program. Specifically excluded are analyses in which the surface pressures result in shear stresses which exceed those due to gravity, and act along the shear surface in the opposite direction. If analyses are attempted with these conditions the factor of safety will tend towards a negative value, and the iterative solution will not converge.

#### Solution Information

96. The user should be familiar with the procedure of analysis used by the computer program. In this procedure of slices, all conditions of static equilibrium are satisfied; the value of the factor of safety and the inclination of the side forces assumed to be parallel, are obtained using an iterative method of solution.

97. Initial values for the factor of safety, FZ, and the side force inclination, THETAZ, should be assumed and specified as input data. These values are then changed by successive approximations on each iteration until the following conditions are satisfied, ie, when the solution converges.

a. Static equilibrium is satisfied within acceptable limits of accuracy. These limits are

specified as input data for the allowed imbalance of forces and moments, FLIMIT and TLIMIT respectively.

- b. The values of the factor of safety and the side force inclination found on successive inclinations are within 0.001 and 0.01 degrees, respectively.

98. If either of these conditions for convergence is not satisfied within an iteration limit, ITERL, specified by the user, the message, "SOLUTION DID NOT CONVERGE," will be printed with the output information, and the analysis of the particular shear surface will be abandoned.

99. Restrictions on the convergence to a correct solution and on the values for the specified input variables, FZ, THETAZ, FLIMIT, TLIMIT, and ITERL, are described below. If the specified values for any of these variables are zero, or appear unreasonable, new values will be assumed by the program. If a factor of safety is successfully determined, a probabilistic analysis may be performed. This is requested by the user via the variable MONT.

#### Factor of Safety

100. The value of the factor of safety is permitted to change by a maximum of only 0.5 on successive iterations. This constraint is placed on the solution to ensure proper convergence. If a very inaccurate estimate is made, however, and specified for the initial value of the factor of safety, FZ, the correct value may not be reached within the iteration limit, and the solution will fail to converge. Similar problems may develop when an automatic search is being performed and a trial shear surface passes through a zone of very high shear strength, such as concrete or a firm rock strata, specified for the purpose of limiting the extent of the critical shear surface. In this case a relatively large value for the factor of safety will be sought, but probably not be reached, by the program. With an automatic search this problem is normally of no practical consequence, and the user should verify that for the shear surfaces where the solution did not converge, the values for the factor of safety are relatively large.

101. In addition to the above constraint on the successive changes in the factor of safety on each iteration, the value of the factor is not permitted to become less than 0.1. While this constraint should be of no practical significance, the solution will not converge when the value of the factor of safety is less than 0.1.

#### Side Force Inclination

102. The angle of inclination of the side forces is referenced to a horizontal plane, and positive values are measured in a clockwise direction. The side force inclination will normally be positive for a right-facing slope and negative for a left-facing slope.

103. In the iteration procedure, the value of the side force inclination is not permitted to change by more than  $10^\circ$  on successive iterations and will be adjusted accordingly by the program when this limit is reached. In addition, the side force is not permitted to reach an inclination steeper than  $85^\circ$ , and if this limit is reached the solution will fail to converge. Either a negative side force inclination for a right-facing slope, or a positive side force inclination for a left-facing slope, will also prevent convergence.

#### Allowed Force and Moment Imbalance

104. The specified values for the maximum allowed force and moment imbalances correspond essentially to the maximum permissible error in static equilibrium. Experience with the program has shown that for most typical slopes, the values of the factor of safety and side force inclination are both accurate to within four significant figures, ie, 0.01% when the allowed force and moment imbalances are 100 lb and 100 lb-ft, respectively. The user is, however, expected to verify the accuracy of his results for the specified limits used. The values for these limits may not be specified as zero because of machine round-off errors.

#### Iteration Limit

105. When reasonable values are assumed for the factor of safety and side force inclination, convergence to a solution is normally attained within



three to ten iterations. This assumes that the factor of safety is estimated to within the correct value by approximately 1.5 and the side force inclination is estimated within 20° of the correct value. If the solution fails to converge within an apparently reasonable number of iterations, the user should examine the step-by-step iteration data printed with the output information for analyses of individual circular and non-circular shear surfaces. For an automatic search this information is given only for the final critical circle.

#### Probability Analysis Input

106. If a probability analysis is desired, the value of MONT on the input card R must be specified as 1. or 2.

107. Input for the probability analysis is divided into four categories: (a) control data; (b) profile data; (c) material data; (d) pressure and piezometric line data. The user can set an input flag so that data can be either retained or changed selectively for each analysis.

108. The ground geometry, material, and pressure/piezometric data sets, if pertinent, must follow the control data in that order, and each data set must terminate with a blank card.

109. The control data consist of flags which determine how the data following it is to be read. Each group of data identifies values to be sampled and the associated probability distribution.

110. In the following section, the input data are described. Exhibit D2 is a tabulated description of input.

#### Control Data

111. The card containing these data must always appear when the input value MONT on card R is equal to 1. The data consist of several items as tabulated in Exhibit D-2. The nature of these items is briefly described below.

112. The sample size, NSAMPL, allows the user to control the number of samplings required to obtain the required level of confidence in the statistics. The larger the sample size the higher the confidence level, but the computation time

increases in proportion. It is, therefore, recommended that 200 be the sample size in a typical problem.

113. The random number seed, MF, is the first element of the random number sequence to be sampled. In the random number generator used in the CDC 6400 version of this program, all subsequent numbers depend on this seed. Results may thus be reproduced, if desired, in subsequent runs.

114. Output options are also specified on this card, ie, MPRT, NX, and BINSIZ. The maximum detail output MPRT=3. should be used with caution as it can produce a page or more of output for each factor of safety calculation, the result being more than 1000 pages of output when NSAMPL=1000. The width of the ideogram plot, ie, factor of safety range vs number of factors of safety found within that range, across the computer page is determined by NX, which can be no larger than 100.

115. BINSIZ determines either the class size, or the number of classes into which the factors of safety are sorted. Specifying the class size BINSIZ < 1. will give cleaner cutoff points for the classes if this is not the case, however, a value of BINSIZ which is too large or too small will produce a plot which may not give a satisfactory resolution of the final distribution curve. This problem can be avoided by specifying BINSIZ ≥ 1., which will then represent the number of classes into which the final distribution will be divided. In determining this value the user should take into consideration both the sample size and the total possible range of the sampled factors of safety.

116. The quantity FC refers to the critical factor of safety below which the slope is assumed to be unstable. This value defaults to 1. if the user leaves the field blank.

117. The last three quantities on this card, ISOIL, IMATR, and IPRES, indicate to the program the type of data which follows.

118. Except for FC, none of the quantities in the probability analysis input data have default values. Therefore, if the user leaves a field

blank, the value passed to the program will be 0.

#### Ground Profile Data

119. The input scheme for sampling ground profile data, essentially the same as the input for pressure/piezometric data, allows the user a great deal of flexibility.

120. One card may be used to sample all the points on one line or only a portion of them. All points specified on one card will have the same type of distribution, and this is also given on that card. These points can be sampled independently or, alternatively one point can be sampled and its deviation from the original average value can be applied to the other points. The latter option will cause a translation of the line or a portion of the line. In addition, the points can vary in either the x or y-directions or both if desired.

121. The maximum number of lines which may be sampled is 20, and each line may reference up to 15 points.

122. It often occurs that a line which is to be sampled is touching a line which is well determined. If they have a point in common the problem is handled in the following way. Before any ground line is varied, a table is set up in the program which identifies those points which have identical (x,y) values, ie, the same points falling on different lines. When a point is sampled or varied, this table is checked for other points in the soil profile which have the same (x,y) values that the sampled point had originally. If there are points which satisfy this condition, their values are adjusted to correspond to the current sampled value. If two lines are intended to meet, but do not have a common point, and one of the lines is sampled, the chances are that they will not meet after the sampling. Some examples are shown in Fig D-4.

123. These examples are intended to demonstrate some of the possible situations and problems that may arise when sampling soil profile data. For ease of understanding, simple examples have been given, in which only one line or line segment has been sampled, but the same program logic applies in all situations. By no means do they cover all

the possibilities, and with a little imagination the user may perform just about any type of variation on soil profile lines that he pleases. The examples are numbered and refer to similarly numbered cases in Fig D-5.

#### Example 1

Initial situation	- three horizontal layers of ground
Uncertainty	- thickness of the middle layer B is uncertain
Method of sampling	- all points of line C were sampled together in the y-direction only
Result	- thickness of layer B has changed

#### Example 2

Initial situation	- three types of ground - lines B and C are touching but do not have a common point
Uncertainty	- shape of line C is uncertain
Method of sampling	- all points on line C were sampled independently in both the x and y-directions
Result	- shape of line C has changed - an area remains between lines B and C in which there is no defined geometry

#### Example 3

Initial situation	- three types of ground - lines B and C are touching and have a common point, ie, $x_{B2} = x_{C2} \quad y_{B2} = y_{C2}$
Uncertainty	- shape of line C is uncertain
Method of sampling	- all points on line C were sampled independently in both the x and y-directions
Result	- shape of line C has changed - Shape of line B has changed, point B2 being modified to agree with C2

#### Example 4

Initial situation	- three types of ground
-------------------	-------------------------

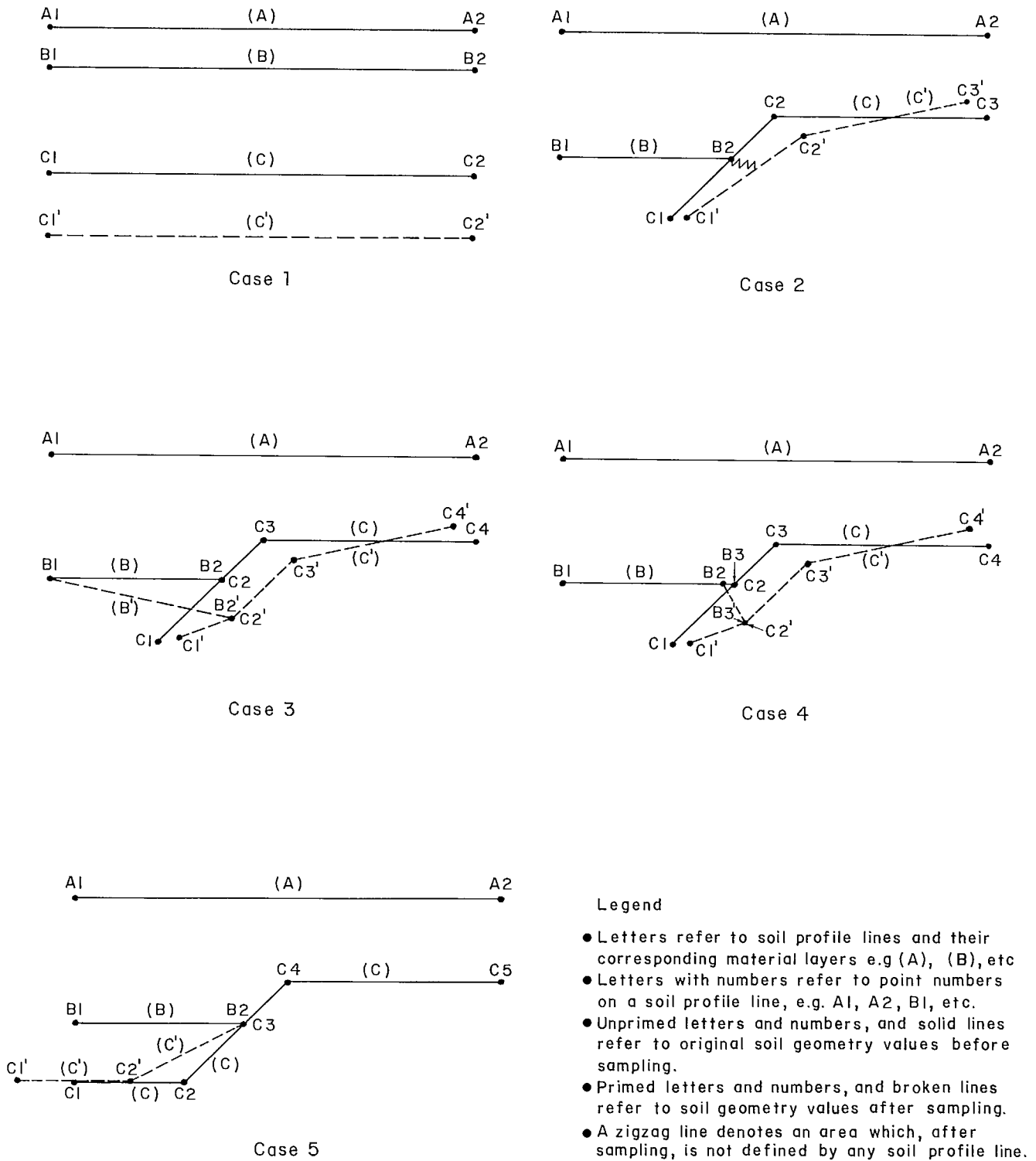


Fig D-5 - Examples of soil profile input for probabilistic analysis.

- lines B and C are touching and have a common point, ie,

$$x_{B3} = x_{C2} \quad y_{B3} = y_{C2}$$

- line B has been determined to be horizontal
- to allow line C to vary in line B, an additional point, very close to the end of the line, has been added to line B

#### Uncertainty

- shape of line C is uncertain

#### Method of sampling

- all points on line C were sampled independently in both the x and y-directions

#### Result

- shape of line C has changed
- a small portion of line B has changed, point B3 having been modified to agree with C2

#### Example 5

##### Initial situation

- three types of ground
  - lines B and C are touching and have a common point, ie,
- $$x_{B2} = x_{C3} \quad y_{B2} = y_{C3}$$
- thickness of layer B is well determined

##### Uncertainty

- slope of line segment C2 → C3 is uncertain

##### Method of sampling

- point C2 was sampled in the x-direction only

##### Result

- slope of line segment C1 → C2 has changed
- thickness of layer B remains the same.

#### Material Data

124. Each quantity in the material data to be sampled must be specified on separate cards along with the distribution. The material type number is the same as given in the original input data, and the variable name within that type, eg, CUPONZ, REFHT, etc, is represented by a code between 1. and 6.

125. For anisotropic ground all C and CUPONZ, when sampled, are varied by the same increment, ie, the quantity C or CUPONZ is sampled at  $-90^\circ$

and the difference between the sampled and original values is applied to those quantities at  $-80^\circ$ ,  $-70^\circ$ , ...,  $+90^\circ$ .

126. In specifying distributions, care should be taken that the values which are bounded at 0., such as GAMMA or unit weight of soil, do not become negative after the sampling. This can be prevented be specified, eg, truncated gaussian, triangular, etc.

#### Pressure Piezometric Data

127. The input format for sampling pressure and piezometric data is basically the same as that of the profile line data. One of the main differences is that, in the case of pore pressure and surface pressure, the values at the points are sampled rather than the x, y points as with profile data. The points themselves are numbered beginning with the first occurrence of that MTYPE, card H, within the pressure input to the program.

128. For example, if there are seven material types and the pore pressure is specified somewhere else in the input, the original surface pressure and piezometric line data may appear as shown in Table D-1.

Table D-1: Input data for pressure/piezometric lines

	Columns			
	1	9	17	25
Card	XPP	YPP	PP	MTYPE
(1) Surface	100.	100.	312.	8.
(2) Surface	200.	100.	312.	8.
(3) Surface	250.	150.	0.	8.
(4) Piez	100.	150.		9.
(5) Piez	250.	150.		9.
(6) Piez	350.	150.		9.
(7) Piez	500.	125.		9.

129. These data imply that there is one set of surface pressures consisting of three points and that the piezometric line is defined by four

points. When specifying the Monte Carlo input data, eg, card 6, will be referred to as the third point in the piezometric line, MTYPE = 9., even though it is the sixth point in the pressure data.

130. The Monte Carlo interface routines will handle up to 30 points in each MTYPE, ie, 30 pore pressure points in each material type, a total of 60 surface pressure points, ie, 30 for MBPL1 and 30 for MBPL2, and 30 points on a piezometric line. An attempt to sample more than this amount will result in incorrect output values.

#### Description of Distribution Types

131. There are five possible distributions which may be used in the probability analysis.

Each is represented in the input by a code between 1. and 5. as shown in Fig D-6.

132. ST1, ST2, and ST3 are the values which must be input to specify the bounds of the distribution, which must all be non-negative. The mean shown in Fig D-6 is taken as the original user input value.

133. The triangular and uniform distributions may have either ST1 or ST2 equal to 0., but not both. An input of ST2 = ST3 = 0. in the truncated gaussian distribution should be avoided as it will cause the program to go into an infinite loop.

#### Sequence of Data Input

134. Input of data into the computer program is

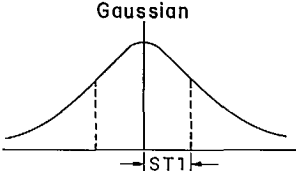
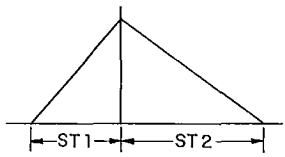
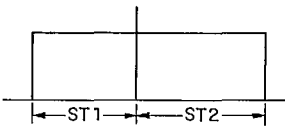
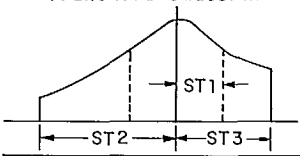
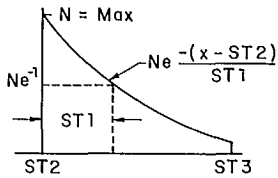
Distribution Type	Code	ST 1	ST 2	ST 3
<b>Gaussian</b> 	1.	Standard deviation	Blank	Blank
<b>Triangular</b> 	2.	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side (positive distance)	Blank
<b>Uniform</b> 	3.	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side (positive distance)	Blank
<b>Truncated Gaussian</b> 	4.	Standard deviation	Maximum distance from the mean to the left (lower) side (positive distance)	Maximum distance from the mean to the right (upper) side (positive distance)
<b>Exponential</b> 	5.	Decay constant	Lower bound measured from 0	Upper bound measured from 0. Leave blank if no upper bound exists.

Fig D-6 - Distribution types and parameters.

separated into three levels as illustrated in Table D-2. For each level of data, several sets of data of a higher level, eg, Level III, may be input without repeating data of Levels I or II. The program also permits data in Levels I-A, I-B, or I-C to be changed without changing the data in all sub-levels of Level I. This partial change of data is made by specifying appropriate values for the codes, KEEP1, KEEP2, and KEEP3. Normally, any change of data in a lower level requires a repetition of all higher level data as input; however, if data are changed in Level I, the previous set of slope coordinate data used in Level II may be saved by specifying the appropriate value for the code KEEP4. If more than one slope was previously analyzed at Level II, only the last slope data analyzed may be saved.

135. Various error messages may be produced, indicating unacceptable input data. The possible messages are given in Table D-3.

Table D-2: Sequence of data input

	Level I - Data cards A through I
	(Number of Level I Inputs = number of soil profiles to be analyzed)
	I-A - Profile Line Data
	I-B - Profile Material Data
Higher Levels	I-C - Pressure Data
	Level II - Data cards J through M
	(Number of Level II Inputs = NSLOPS)
	II - Slope Geometry Data
	Level III - Data cards N through R or DD
	(Number of Level III Inputs = NSTART)
	III-A - Trial Shear Surface or Search Data
	III-B - Data for Probability Analysis if desired

136. A more detailed description of the sequence and format of data input is included in Exhibit D-1.

#### OUTPUT

137. The printed output information from the computer program includes the specific input data, intermediate data generated during computation, the final solution data and probability analysis output. The printing of portions of this information may be controlled by the user by specifying as input data appropriate values for the codes, ISUP, ISUP1, ISUP2, and for the probability output, MPRT. The default output in the deterministic case includes all of this information and should be carefully checked to verify the correctness of a solution. Only in special cases should any portion of the output be suppressed. Output for the probabilistic case is described in a separate section. The default mode produces the minimum amount of printout.

#### Input Data

138. All of the input data are printed as part of the computer output. These data are printed in a self-explanatory format and in the same general sequence in which they are specified as input. When several sets of data of a higher level, eg, Level III referred to in Table D-2, are specified, the data specified in the lower Levels I and II, are not repeated and are printed only once.

139. The printing of input data in Levels I and II is controlled by the specified value of the code, ISUP. Level III input data are always printed.

#### Intermediate Data

##### Search Option

140. When an automatic search is being performed, one line of output is printed for each trial circle attempted. This information includes the centre coordinates and radius of the circle, the factor of safety and side force inclination, and the number of iterations required to obtain the solution. If computation errors are encountered, additional lines of output will be printed,

Table D-3: Input data error messages

Error message	Explanation
XXX PROFILE LINES ARE NOT ALLOWED	The specified number of soil profile lines is either less than 1 or exceeds the dimensioned capacity of the program.
XXX PROFILE POINTS FOR PROFILE LINE XXX ARE NOT ALLOWED	The number of coordinates specified for the profile line indicated is either less than 2 or exceeds the dimensioned capacity of the program.
DATA FOR PROFILE LINE XXX, POINT XXX, IS OUT OF ORDER	For the profile line and coordinate point indicated, the x-coordinate is less than, or equal to, the x coordinate of the previous point.
KODEP - XXX (MATERIAL XXX) IS AN ILLEGAL CODE	For the material type indicated, the specified value of the pressure code KODEP is either negative or is greater than 5.
KEY = XXX (MATERIAL XXX) IS AN ILLEGAL CODE	For the material type indicated, the specified value of the code, KEY, is either negative or is greater than 2.
XXX PORE PRESSURE, SURFACE PRESSURE, AND PIEZOMETRIC LINE DATA POINTS NOT ALLOWED	The specified number of Pressure Points is either less than 2 or exceeds the dimensioned capacity of the program.
SLOPE POINT XXX (X = XXX, Y = XXX) IS OUT OF ORDER	The x coordinate of the slope point indicated is less than the x-coordinate of the previous slope point.
THETA = XXX AND ARCMAX = XXX ARE NOT ALLOWED	Both values are zero or one of these parameters has a negative value. Slices can only be generated when one of these parameters has a positive value and the other is equal to zero.

Error message	Explanation
ERROR IN PRESSURE OR PIEZOMETRIC LINE DATA POINT XXX X = XXX Y = XXX MTYPE = XXX UNDEFINED	<p>The value of MTYPE must be equal to one of the following:</p> <ul style="list-style-type: none"> <li>a) the number of one of the material types, from 1 to NMATS;</li> <li>b) the value of MBPL1 or MBPL2;</li> <li>c) the value of NPIEZ.</li> </ul> <p>If the value of MTYPE is not equal to one of the above values, this error message will be given for the data point indicated.</p>
XXX MATERIALS NOT ALLOWED	The specified number of materials is either less than 1, or exceeds the dimensioned capacity of the program.
FOR PROFILE NO. XXX, MATERIAL TYPE XXX DOES NOT EXIST	The specified material type for the profile line indicated is either less than 1 or exceeds the specified number of materials.
NO SURFACE PRESSURE DATA	The program has attempted to utilize surface pressure data; all pressure data cards, however, were for pore pressure or $r_u$ interpolation values.
MTYPE = XXX IS INCORRECT FOR SURFACE PRESSURE DATA	The indicated value of MTYPE is not equal to either MBPL1 or MBPL2. The required sequence of pressure data cards has probably not been followed.
NO PIEZOMETRIC ELEVATION DATA	The program has attempted to utilize piezometric elevation data; however, either all pressure data cards were for pore pressure and $r_u$ interpolation values and for surface pressures, or no pressure data cards were specified.
MTYPE = XXX IS INCORRECT FOR PIEZOMETRIC ELEVATION DATA	The indicated value of MTYPE is not equal to the value specified for NPIEZ; the required sequence of pressure data cards has probably not been followed.



Error message	Explanation
ITYPS = XXX IS AN INCORRECT CODE	The indicated value of ITYPS is not equal to 1, 2, or 3; these are the only acceptable values for the option code.
NCORDS = XXX EXCEEDS LIMIT OF X	The indicated number of non-circular shear surface coordinates specified is either less than 2, or exceeds the indicated dimensioned capacity of the program.
S.S. COORDINATE NUMBER XXX, X = XXX, Y = XXX, IS OUT OF ORDER	Either the indicated coordinate which has been specified for a non-circular shear surface does not follow the sequence of points from left to right, or a vertical segment has been specified for the shear surface.
XXX FEET REQUIRED ACCURACY IN CRITICAL CIRCLE CENTRE NOT ACCEPTABLE	A zero or negative value for ACC is not allowed in the program.
ICIRCL - XXX IS INCORRECT SEARCH MODE	The specified code for the initial mode of search either is less than 1 or is greater than 2.

including the circle coordinate and radius data with the appropriate error message listed in Table D-4.

141. For each mode of search, the appropriate heading and information used by that mode are printed. Depending on the mode of search, this may include the elevation of the hypothetical rock line, Mode 1, the coordinates of the fixed point through which all circles pass, Mode 2, or the fixed radius used, Mode 3. Printing of this information and the single line of output for each circle is controlled by the specified value of the code, ISUP1. If computation errors occur, however, the circle data and error message will always be printed regardless of the value of ISUP1.

#### Individual Shear Surfaces

142. When individual shear surfaces are specified, the information for the individual slices is normally printed with the output. This includes for each slice, the coordinates along the shear surface at the left, centre and right of the base, the weight, the cohesion or undrained shear strength, angle of internal friction, pore water pressure at the base, and the magnitude and point of action, expressed as an x-coordinate, of the resultant force due to surface pressures acting at the top of the slice. The printing of this information is controlled by the specified value of the code, ISUP2.

143. When a non-circular shear surface is specified, the program will usually define additional

Table D-4: Computation error messages

Options Relevant ITYPES	Action*	Error message	Explanation
A11		ERROR FOR SLICE XXX X = XXX Y = XXX	An error was first detected for the slice indicated. The x and y-coordinates correspond to the centre of the base of the slice. A more detailed error message will always follow.
A11	(A)	COORDINATES OUTSIDE SLOPE DATA	The coordinates for the trial shear surface were beyond the extent of specified slope data.
A11	(A)	ATTEMPT TO STORE XXX PROFILE INTERSECTIONS	The number of profile lines crossing a slice exceeded the dimensioned capacity of the program.
A11	(F)	NO PROFILE DATA FOR TOP OF SLICE	Profile lines were not defined for all soil beneath the slope.
A11	(F)	6 INTERPOLATION POINTS NOT AVAILABLE FOR PORE PRESS.	Insufficient data points were specified for interpolating pore pressures or values of $r_u$ . At least 6 points must be specified in each material where pore water pressures are obtained by interpolation.
A11		NO 4 POINT REPLACEMENT POINT FOR PRESS. INTERP. - 3 PTS. USED	Interpolation for pore pressures using 4 adjoining points was not possible. Thus, 3 points were used.
A11	(A)	PRESS. INTERP. NOT POSSIBLE	Interpolation for pore pressures was not possible using either 3 or 4 points. The geometric configuration of the specified points should be changed.
A11	(F)	ERROR IN SURFACE PRESSURE DATA	The coordinates of the surface pressure data points were either not coincident with the lines specifying the slope geometry, or points were not specified at breaks in the slope geometry.

Options		Error message	Explanation
Relevant	Action*		
A11	(A)	LINEAR INTERPOLATION OF UNDRAINED STRENGTH NOT POSSIBLE - NO LINE FOR STRENGTH BELOW BASE OF SLICE.	Strength can be interpolated only between two profile lines having identical values for code KI. If only one such line is specified, or if the shear surface passes below the lowest line of a group and no other profile line is encountered, this message will be given.
A11	(A)	INSUFFICIENT PIEZOMETRIC ELEVATION DATA	The coordinates of the shear surface, where pore pressures were to be determined from the piezometric elevation data, were beyond the limits of the piezometric line coordinates.
1,3	(A)	CIRCLE DOES NOT INTERSECT SLOPE	This message is the result of one of the following: a) The centre of the circle is beneath the slope. b) The centre point and radius result in a circle which does not intersect the slope. c) Only one slice was generated for the circle.
A11	(A)	STORED COORDS. EXCEED XXX	The program requires some specific coordinates along the shear surface. These coordinates are determined and stored temporarily. If the number of coordinates stored, some of which may be duplicates, exceeds the dimensioned capacity of the program, this error will be given.
1,3		SPECIFIED SLICE GENERATION DATA RESULTS IN OVER XXX SLICES - OLD VALUES DOUBLED FOR THIS CASE	The number of slices exceeded the dimensioned capacity of the program. The specified value of THETA or ARCMAX was doubled.

Options			
Relevant ITYPES	Action*	Error message	Explanation
A11	(A)	XXX REQUIRED COORDINATES EXCEED LIMIT OF XXX	The minimum number of slice coordinates along the shear surface, which the program requires for computation, exceeded the dimensioned capacity of the program.
1,3	(A)	DEPTH OF TENSION CRACK IS GREATER THAN DEPTH OF CIRCLE	The circle is assumed to intersect the base of the tension crack; however, if the condition noted by the error message pertains, intersection is not possible and the error message is given.
3	(AS)	CRITICAL CENTRE COULD NOT BE FOUND AFTER USING XXX GRIDS	The centre of the critical circle could not be located for the current mode of search after trying the indicated number of grids.
3		***CAUTION - F COULD NOT BE COMPUTED FOR SOME OF GRID POINTS AROUND MINIMUM	The search was completed when the centre of the last 9-point grid having a point spacing equal to the specified value of ACC, had a factor of safety which was lower than those for the remaining points in the grid. However, not all values of the factor of safety for these remaining centres could be computed, as indicated by previous error messages. Thus, the indicated location of the critical centre <u>may not be correct.</u>
3	(AS)	XXX SECS. EXCEEDS TIME LIMIT OF XXX	The time required to locate the critical circle for a particular problem exceeded the specified time limit. The problem was abandoned and the next problem was attempted. It should be noted that elapsed time is checked only prior to changing the mode of search.

Options			
Relevant ITYPES	Action*	Error message	Explanation
A11	(A)	SOLUTION DID NOT CONVERGE	Either the factor of safety could not be computed within the specified number of iterations, or the solution was not converging properly.
3		CENTRE OF CIRCLE IS OUTSIDE OF GRID - CIRCLE REJECTED - GRID RELOCATION INITIATED	The dimensioned capacity of the array used to store the computed values of the factor of safety for trial circles was exceeded. The array was re-initialized and the search continued. The final results are not affected by this condition.
3	(A)	UNACCEPTABLE RADIUS - REJECTED	The radius of the trial circle was either less than, or equal to zero, or exceeded 100,000.
3	(AS)	***** ALL GRID POINTS HAD AN INDETERMINATE F - SEARCH ABORTED	The factor of safety could not be computed for any of the circles whose centres were points in the last 9-point grid. Previous to this message, other errors will be listed which give the reasons for the factors of safety not being computed.
3		***** SPECIFIED STARTING POINT FOR GRID IS NOT OPTIMUM - RESET BY PROGRAM	The estimated coordinates for the centre of the critical circle were probably at least a distance equal to 20 times ACC, the specified accuracy in the location of the critical centre away from the location of the actual critical centre. This message is for the user's information only and does not necessarily indicate that the critical centre be found.

\* (A) = trial surface abandoned, next surface attempted

(AS) = problem abandoned, next problem attempted

(F) = execution terminated.

coordinates along the shear surface. These coordinates are required for computation, and the new coordinates, including those which were specified, are always printed and appear before the general slice information.

144. When an individual shear surface is specified for analysis, the step-by-step iteration data will always be printed and will follow the individual slice information. The iteration data will include for each iteration, the assumed values for the factor of safety and side force inclination, the computed force and moment imbalances and the computed adjustments required for the current values of the factor of safety and side force inclination. These adjustments are used on the next iteration.

#### Final Solution Data

145. Upon completion of an automatic search, the coordinates and radius of the critical circle are printed with the corresponding values for the factor of safety and side force inclination. Following this output, the critical circle is automatically specified again and analyzed as a single individually specified, circular shear surface. Consequently, all output information normally printed for an individually specified circle is then printed for the most critical circle.

146. Once the factor of safety has been computed for an individual shear surface or for a critical circle located in a search, a table of computed stresses and equilibrium forces is printed. This information includes the normal and shear stresses on the base of each slice, and the magnitude and position of the normal component of the side force at the right of each slice. The position of the side force is given in terms of the y-coordinate of its point of action, YT, and the relative distance, FRACTION, above the base of the slice, relative distance being specified as a decimal fraction of the vertical depth of the shear surface.

#### Probability Analysis Output

147. The probabilistic analysis output always contains a printout of the user input data. The value of MPRT described in Exhibit D-1 determines

the degree of detail which will be printed during the sampling of safety factors. The maximum output option, MPRT = 3., should be used with care, as the printout will contain all data sets with sampled values which go into the calculation of the factors of safety. For example, even if only one line were sampled, the entire set of profile lines will be printed each time.

#### ERROR MESSAGES

148. The computer program includes two types of program error messages, one for input data errors and the other for those generated during computation. The input data errors are listed in Table D-3 with a brief explanation of each; if any of these are encountered in the program, execution will be terminated.

149. During computation a number of additional error checks are made by the program, and one or more of the error messages listed in Table D-4 may be given. These errors may result in fatal termination of the program execution, abandonment of only the particular trial shear surface or of the search for the critical circle for a particular slope problem, or in normal continuation of program execution. The action taken by the program subsequent to each error is included in Table D-4 in the column titled, "Options." This column gives the values of ITYPS to which the error is applicable. The letter or letters in parentheses following the option designation indicate the error type as follows.

A - the trial shear surface is abandoned and the next surface is considered.

AS - the search is abandoned for this problem and the next problem is attempted.

F - execution of the program is terminated and no further computations are attempted.

150. If no letter follows the option designation, the error message is only an informative or warning message and execution proceeds in a normal manner.

#### EXAMPLES

##### Deterministic Case

151. The following illustrates a series of

analyses of the slope of an embankment shown in Fig D-7. In this example the embankment and foundation are divided into 11 zones and 11 material types. The number of each zone, followed by the number or range in numbers, of the material types associated with the zone, are given in parentheses in Fig D-7. The input data for this problem are listed in Exhibit D-2.

### Profile No. 1

- Card A: Job No., user's initials, date of run and title "EXAMPLE PROBLEM A - SOIL PROFILE No. 1" are written on this card.
- Card B: A blank card is provided for ISUP = ISUP1 = ISUP2 = 0, for normal printing codes.
- Card C: Thirteen profile lines - one for the top of each of the 11 zones shown in Fig D-7, plus two additional lines for contours of constant shear strength in

Zone 10 - and 11 material types are required. The value of MBPL1 is equal to 12, ie, 11 + 1, and the value of MBPL2 is equal to 13, ie, 11 + 2. The piezometric line which is specified for Zones 1, 2, and 4 will require a value for NPIEZ which must be equal to 14, ie, 11 + 3. The unit weight of water need not be specified, ie, can be left blank. The values of KEEP1, KEEP2, and KEEP3 are equal to zero since this is the first problem analyzed.

Cards D and E: The first profile line specified is that at the top of Zone 1. This line has three coordinates and is associated with Material Type 1. Additional profile lines are specified in the same sequence as selected for zone numbering; Zone 10, however, requires three profile lines which are specified from the surface downward. The profile line at the

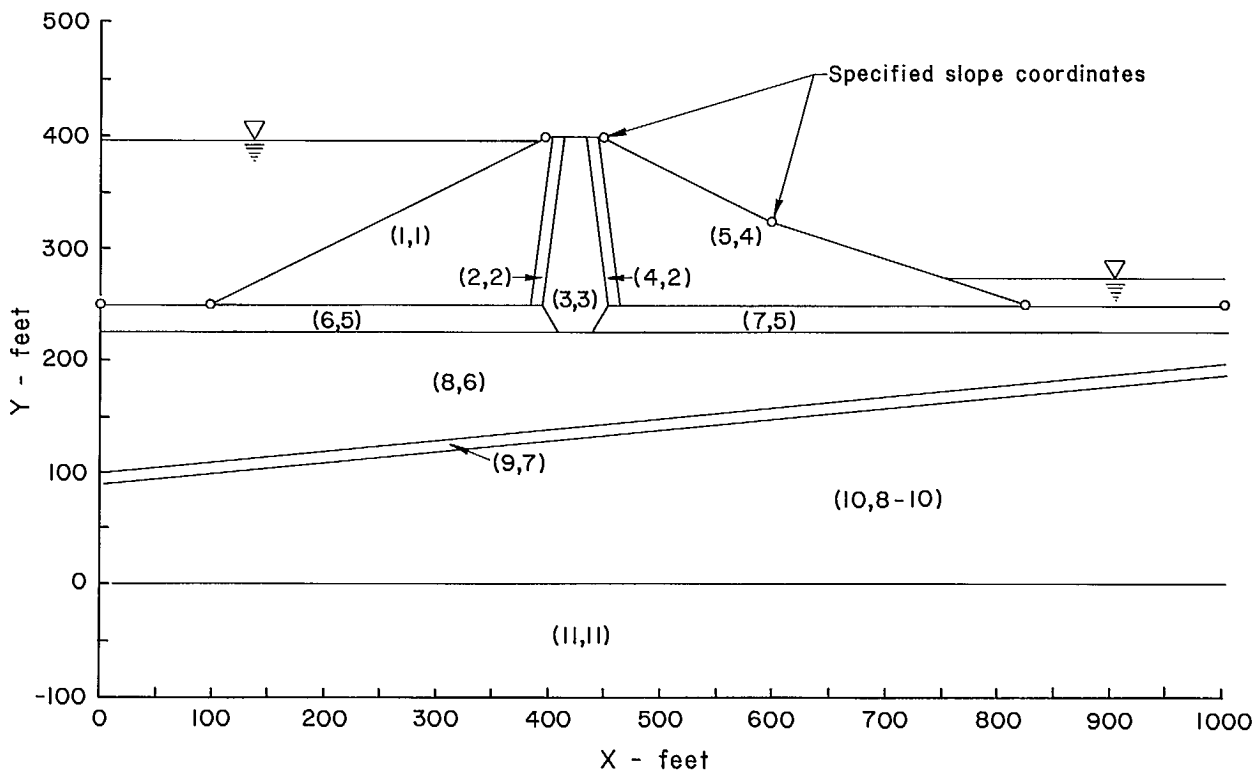


Fig D-7 - Profile cross-section for example A.

bottom of Zone 10 is specified twice, once for Zone 10 and once for Zone 11.

Card F: The characterizations of shear strengths and pore water pressures differ for each material type as below:

Material Type 1: This material, located in Zone 1, is a cohesionless soil having an angle of internal friction of 40 degrees and a unit weight of 135 lb/cu ft (21.4 kNm<sup>3</sup>). Pore water pressures are determined from the piezometric line.

Material Type 2: This material, located in Zones 2 and 4, is a cohesionless material with an angle of internal friction of 35 degrees and a unit weight of 130 lb/cu ft (2.07 t/m<sup>3</sup>). Pore water pressures are determined from the

piezometric line.

Material Type 3: The clay core material has a cohesion of 800 psf (38.3 kN/m<sup>2</sup>), an angle of internal friction of 25 degrees, and a unit weight of 120 lb/cu ft (1.91 t/m<sup>3</sup>). Pore water pressures are expressed in terms of a constant value of  $r_u$  equal to 0.30.

Material Type 4: The material in the downstream slope has a cohesion of 500 psf (24.0 kN/m<sup>2</sup>), an angle of internal friction of 26 degrees, and a unit weight of 123 lb/cu ft (1.96 t/m<sup>3</sup>). The pore water pressures are determined by interpolation of values of  $r_u$  from values which are specified at 31 selected points, shown in Fig D-8.

Material Type 5: The undrained shear

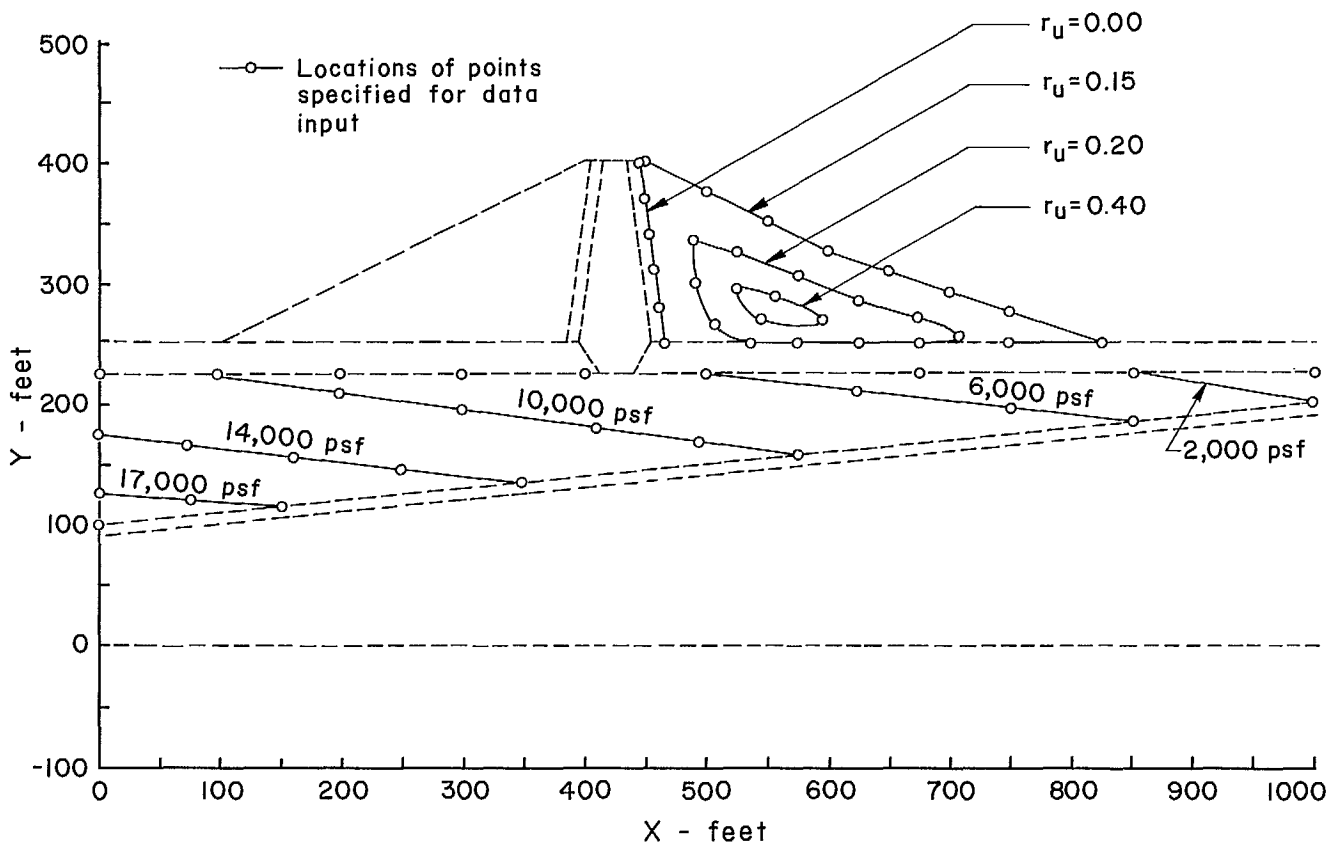


Fig D-8 - Pore water pressure and  $r_u$  values used for example A.



strength of this material is anisotropic, varying with the orientation of the failure plane in the manner shown in Fig D-9. The unit weight of the soil is 120 lb/cu ft (1.91 t/m<sup>3</sup>), and the pore water pressures are zero, as is appropriate for this form of shear strength characterization. Nineteen data cards are required for this material.

Material Type 6: This material type corresponds to the soil in Zone 8. The soil has a cohesion of 350 psf (16.8 kN/m<sup>2</sup>), a friction angle of 28 degrees, and a unit weight of 115 lb/cu ft (1.83 t/m<sup>3</sup>). The pore water pressures are determined by interpolation, using the specified pressures at the points indicated in Fig D-8. These points were selected to represent the pore pressure contours shown in this figure.

Material Type 7: The undrained shear strength of the soil in Zone 9 increases with depth. The strength at a Y-

elevation of 200 ft (61 m) is equal to 2000 psf (95.8 kN/m<sup>2</sup>), and the strength increases at the rate of 10 psf per ft (1.57 kN/m<sup>2</sup>/m) of depth below this level. The unit weight of soil is 125 lb/cu ft (1.99 t/m<sup>3</sup>), and the specified pore pressures are zero, as is appropriate for this form of strength characterization.

Material Types 8 through 10: The data for these three material types correspond to the strengths along the three profile lines associated with Zone 10. As shown in Fig D-10, the undrained shear strength along these lines, proceeding from top to bottom, is 8000, 10,000 and 11,000 psf (383.2, 479.9 and 526.9 kN/m<sup>2</sup>), respectively. The unit weight of the soil is equal to 126 lb/cu ft (2.00 t/m<sup>3</sup>) and is constant throughout the zone. The specified pore pressures are zero, as is appropriate for this form of strength characterization,

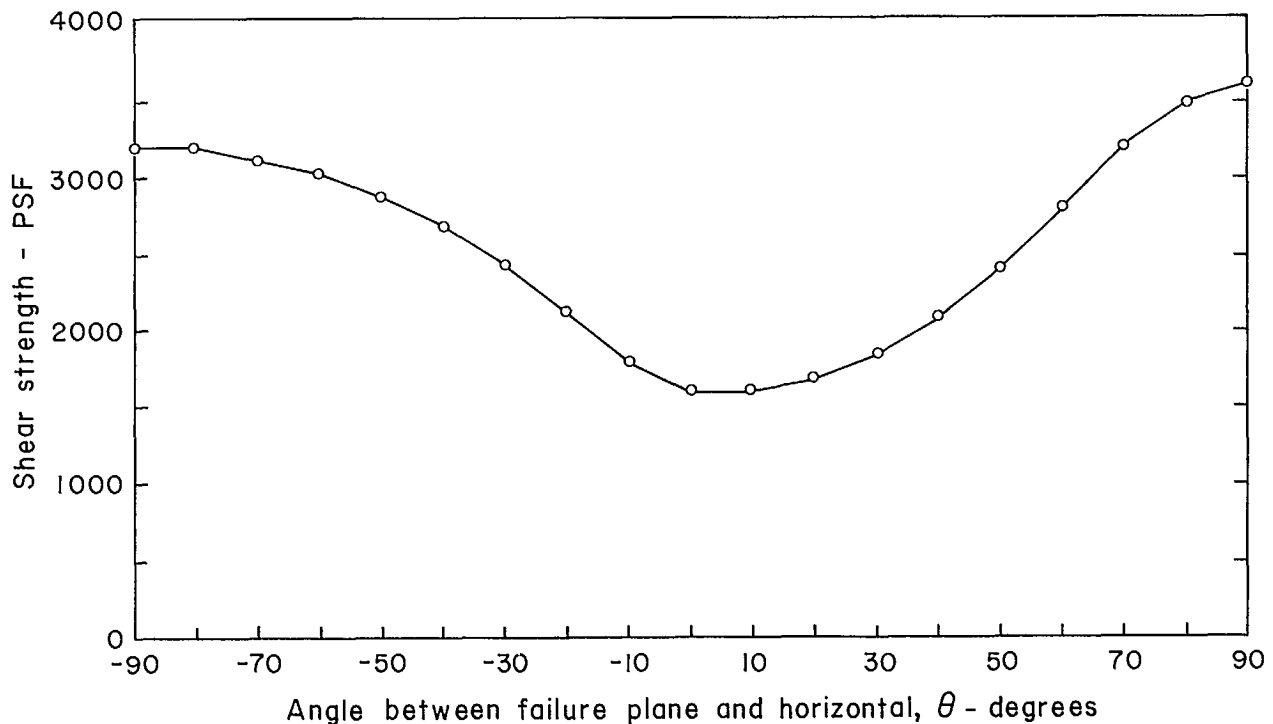


Fig D-9 - Variation in undrained shear strength for material type 5, example A.

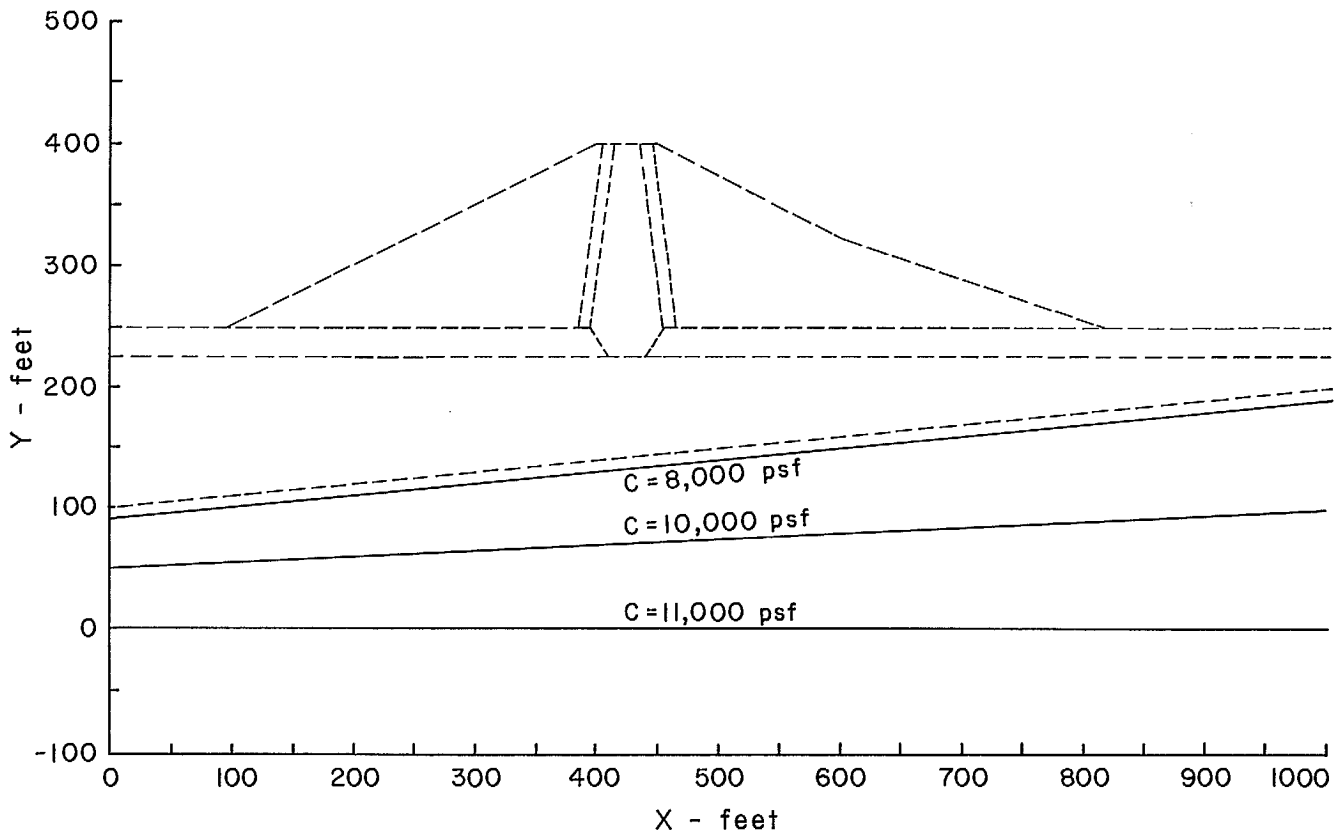


Fig D-10 - Strength contour lines for zone 10, example A.

and the arbitrarily selected value of  $KI$  is equal to 9 for each of these three material types.

Card G: Sixty-eight pressure data points are specified. These include 31 values for  $r_u$  used for interpolation in Zone 5, 27 values for pore pressure used for interpolation in Zone 8, 6 values for the water pressure on the surface of the slope and 4 points on the piezometric line.

Card H-1: The selected values of  $r_u$  in Zone 5 and the selected values of pore pressure in Zone 8 are specified under this format. The contours of  $r_u$  and pore pressure in these zones are illustrated in Fig D-9 along with the specific points at which the selected values are input.

Card H-2: The water pressures acting on the surfaces of the upstream and downstream portions of the embankment and foundation are specified on these data cards.

Card H-3: The piezometric line data required for Zones 1, 2, and 4 are specified on these data cards. On the upstream side of the core, Zones 1 and 2, the piezometric level is the same as the reservoir water level. In Zone 4, on the downstream side of the core, the piezometric level is at the bottom of the zone.

Card I: The number of slopes is one.

Card J: The selected slope title is, "EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT."

Card K: Seven coordinates are required to define the embankment and ground surface geometry.

Card L: The specified slope coordinates are indicated in Fig D-7.

Card M through Q: Three analyses are performed for the first soil profile-slope configuration. The analyses are performed in the order described below:

Analysis No. 1: The factor of safety for the single circular shear surface shown in Fig D-11, is computed. The centre of the circle is located at the coordinates, in feet  $x = 700.0$ ,  $y = 500.0$ , and the circle passes through the point whose coordinates are  $x = 950.0$ ,  $y = 250.0$ . The circle is subdivided into slices by using arc lengths of 25 ft (7.6 m).

Analysis No. 2: A critical circle is

found by first locating the most critical circle which is tangent to a horizontal line at the elevation  $y = 200.0$  ft (61 m). The estimated coordinates of the centre of the critical circle are  $x = 650.0$ ,  $y = 450.0$ , and the accuracy desired in locating the centre of the critical circle is 10 ft (3.05 m). All circles are subdivided into slices by using arc lengths which subtend an angle of 4 degrees between radii of the circle. The critical circle is not allowed to pass below the elevation  $y = 50.0$ . It should be noted, however, that the profile line and slope coordinate data have not been specified at sufficient distances to the right to

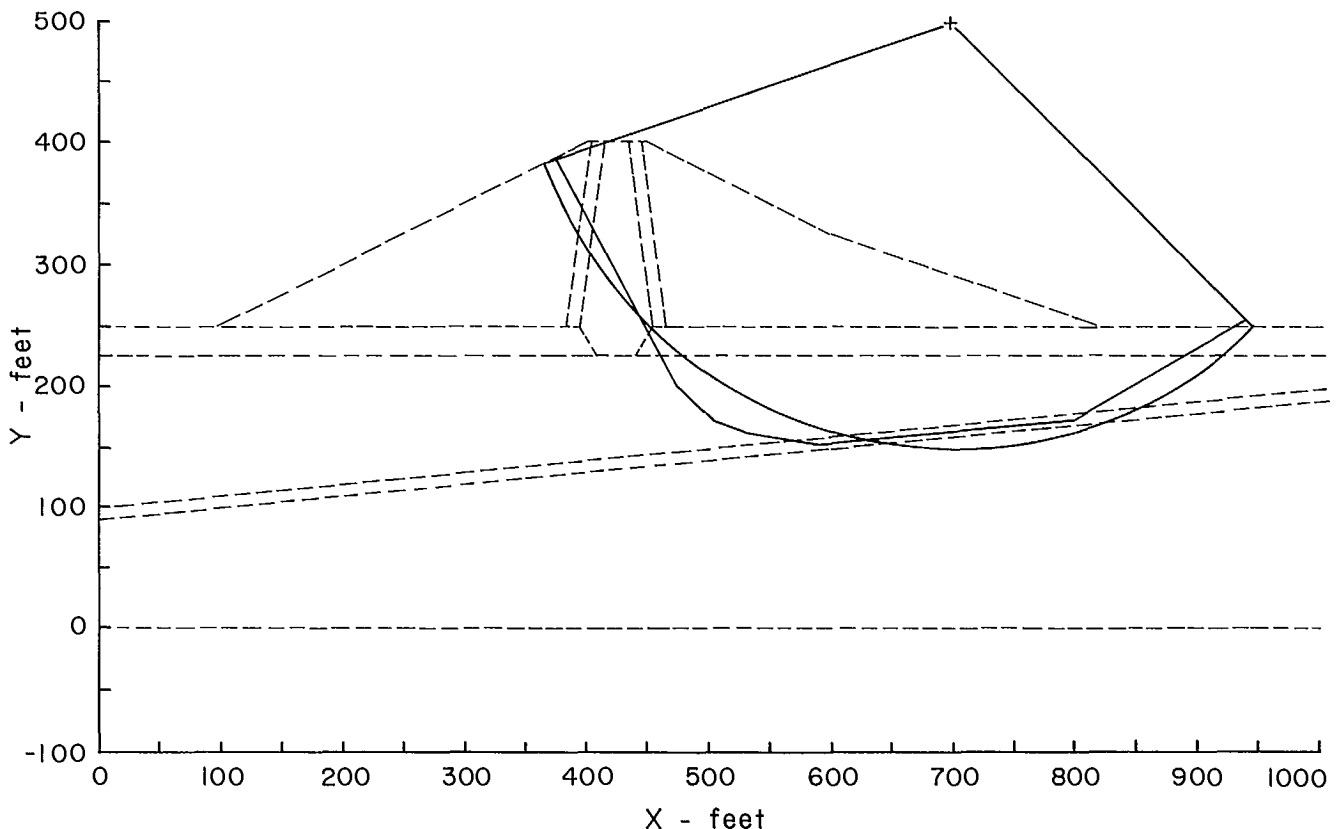


Fig D-11 - Individual circular and non-circular shear surfaces analyzed, example A.

permit most circles to intersect the slope when the circles pass to depths as great as the specified limit. It should also be noted that the most critical circle found for this analysis may not be the most critical circle of all, because of the probable existence of localized areas with individual minimum factors of safety.

Analysis No. 3: The factor of safety for the non-circular surface shown in Fig D-11, is computed. The geometry of this surface is specified by nine coordinates.

Card R: For each of the three analyses described above, the initial values assumed for the factor of safety and side force inclination are 2.5 and 20 degrees, respectively. A maximum of 30 iterations is permitted to satisfy force equilibrium within 100 lb (445 N) and moment equilibrium within 200 lb-ft (272 Nm).

#### Profile No. 2

152. The second soil profile analyzed is the example earth dam illustrated in Fig D-7, and the geometry is identical with Profile No. 1. The characterizations of shear strengths and pore water pressures have been modified in several zones as described below.

Card A: The profile title is, "EXAMPLE PROBLEM A - SOIL PROFILE NO. 2."

Card B: Blank card for normal printing options.

Card C: The number of profile lines and material types is the same as used for Profile No. 1, and both surface pressure and piezometric line data are required. Thus, the data on this card are identical with the data for Profile No. 1, with the exception of the code, KEEP1. The profile line data will remain unchanged, while new strength and pressure data are supplied.

Cards D and E: These cards are omitted and data for Profile No. 1 are used.

Card F: The data for all 11 material types must be specified because the program does not permit a partial change in material data.

Material Types 1-3: No change.

Material Type 4: The shear strength parameters and unit weight of the soil are not changed. A constant value of  $r_u$  equal to 0.25, is used, however, in place of the values obtained by interpolation.

Material Type 5: The characterization of the undrained shear strength is changed from anisotropic to isotropic. A value of 2500 psf (119.8 kN/m<sup>2</sup>) is used for the shear strength and the unit weight is unchanged.

Material Type 6: The shear strength parameters and unit weight of the soil are not changed. The pore water pressures are computed from the piezometric line rather than by interpolation.

Material Types 7 through 11: No change.

Card G: Ten pressure data points are specified. These include six values for the water pressure on the surface of the slope and four points on the piezometric line. No data are required for determination of pore water pressures by interpolation.

Card H-1: This card is omitted as no point values for pore pressure or  $r_u$  are required.

Card H-2: The water pressures acting on the slope are identical with those for Profile No. 1.

Card H-3: The piezometric line data on these cards must be specified for the full lateral extent of Zone 8. The piezometric surface is horizontal and coincides with the upstream reservoir level as far as the boundary between Zones 2 and 3. From this point the piezometric surface slopes linearly downward to the point of intersection between the downstream water level and the embankment surface. To the right of this point, the piezometric surface is coincident with the

downstream water level.

Card I: The number of slopes analyzed is one.

Card J: The selected slope title is, "EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT."

Card K: Seven coordinates are required to define the slope geometry. Since the previously specified slope geometry is identical to the present geometry, however, the coordinates do not need to be specified again.

Card L: Slope coordinate data are omitted.

Cards M through R: For Profile No. 2, only one analysis is to be performed. The most critical circle passing through the downstream toe of the embankment is to be located. The estimated coordinates, in feet for the centre of the critical circle are  $x = 650.0$ ,  $y = 475.0$ , and the desired accuracy for the location of the centre of the critical circle is 10 ft (3.05 m). All circles are subdivided into slices by using arc lengths which subtend an angle of 3 degrees between the radii of the circle. The assumed values for the factor of safety and side force inclination, the allowed force and moment imbalances, and the iteration limit are the same as the values used for the analyses of Profile No. 1.

Card S: END is punched to indicate end of analysis.

The output information for this problem are included in Exhibit D-2.

#### Probabilistic Case (Problem B)

153. A proposed rock slope lies within competent rock underlying a surface layer of alluvium. A fault of large extent filled with clay gouge was found within the rock mass. It is believed that this fault undermines the stability of the proposed slope by forming part of a possible sliding surface. A cross-section of the proposed slope and the assumed sliding surface, as inferred from diamond drilling and from surface mapping of the area, is shown in Fig D-12. More specifically, the following are shown in the figure:

- proposed slope profile defined by seven points denoted by L,G,H,M,N,O,B;
- assumed sliding surface defined by four points, G,P,Q,R;
- assumed tension crack defined by two points, R,O;
- an estimated piezometric line defined by five points, G,H,I,J,K; and
- three soil profile lines for the various soil and rock types AB, CD, EF, are each defined by two points.

154. The location of the piezometric line is estimated from measurements of the piezometric head at several locations, ie, the points H,I,J, and K in Fig D-12. It is believed that the piezometric head at locations between the point H

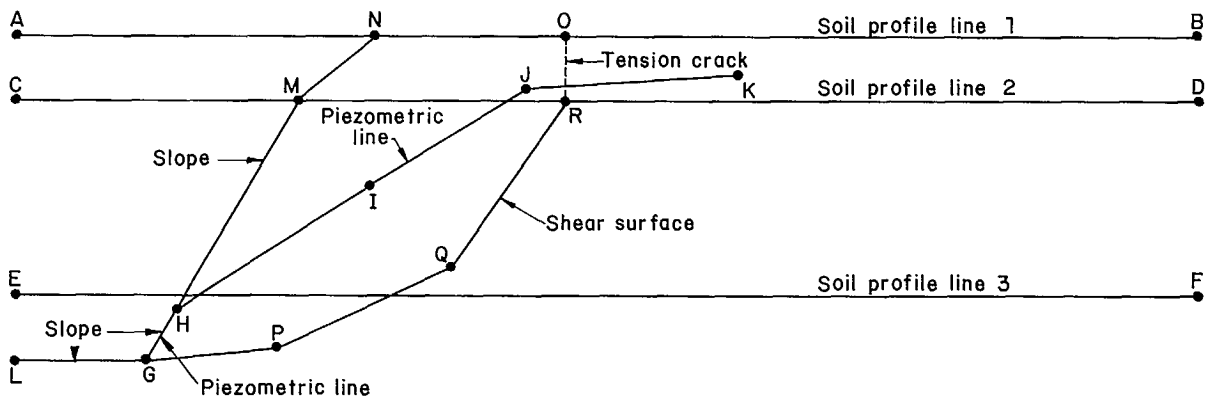


Fig D-12 - Profile cross-section for example B.

and J can be approximated by two line segments such as HI and IJ, but that the location of the point I about the assumed mean is uncertain.

155. The alluvium layer is represented by the zone between the line AB and the line CD. As required by the program, its properties are associated with soil profile line 1.

156. The rock beneath the top alluvium layer is artificially represented by two layers, ie, soil profile line 2 and soil profile line 3. The exact location of the profile line 3 is uncertain, implying that the thickness of the competent rock layers is also uncertain.

157. Although the shear strength of the alluvium is specified in the input data, it is not used in the analysis, as a tension crack is assumed to extend through this layer. Since a limiting equilibrium solution is used, there is no provision in the program for the progressive development of a tension crack. Consequently, the tension crack is assumed to exist already, and the tensile strength of the material is not used by the program. The unit weight of the alluvium is, however, required.

158. Care should be taken in specifying the shear strength properties of soil profile lines 2 and 3, since the sliding surface is assumed to pass through the rock mass as well as along the fault, QR. Thus the rock mass strength has to be specified, together with the shear strength of the clay gouge filling the fault.

159. Sampled values of the unit weight and shear strength parameters, ie, cohesion and friction angle, were found to be normally distributed.

160. The values shown in Table D-5 were obtained, assuming that the cohesion and friction angle are statistically independent.

161. The mean friction angle for soil profile line 2 is five standard deviations from zero. Although the chance of sampling any value less than zero is small, it is still necessary to use a truncated distribution, in this case a truncated normal.

162. Because of the significant variability of the input data, it is desired to obtain the distribution of the factor of safety values and

consequently the reliability for the slope. The input data described below are given in Exhibit D-3.

#### Basic Input

Card A: Title card for analysis.

Card B: The normal mode, complete printout, is selected so that all print options are operating.

Card C: Three different material types are present in this slope. There are no surface pressures, but there is a piezometric line.

Card D and E: Each soil line is horizontal and defines a separate material type.

Card F:  $c$ ,  $\phi$ , and  $\gamma$  values for each material type are specified. In all cases pore pressure is defined by the piezometric line.

Card G: The piezometric line is defined by 5 points.

Card H: Piezometric line coordinate points.

Card I: One slope is analyzed.

Card J: Title of slope.

Table D-5: Material properties for  
probabilistic example

	Unit weight pcf (kN/m <sup>3</sup> )	Cohesion psf (kN/m <sup>2</sup> )	Friction angle degrees
<u>Profile Line 1 (Alluvium)</u>			
Mean	135 (21.465)	0	45
Standard Deviation	15 (2.385)	0	4
<u>Profile Line 2</u>			
Mean	160 (25.440)	350 (16.765)	25
Standard Deviation	15 (2.385)	35 (1.676)	5
<u>Profile Line 3</u>			
Mean	160 (25.44)	400 (19.16)	30
Standard Deviation	20 (3.18)	40 (1.916)	3

Card K: Seven coordinate points define the slope.

Card M: One sliding surface in this slope is analyzed.

Card N: The sliding surface is not circular.

Card P: The sliding surface is defined by four points. Depth from the top of the slope to the water line is 12 ft. The sliding surface coordinate points are also included.

Card R: The initial assumptions for the factor of safety and side force inclination are 1. and -20. degrees, respectively. The maximum limit for both the force and moment imbalance, once a solution is obtained, is 10 lb (44.5 N). A probability analysis is done if the program converges successfully to a value for factor of safety.

#### Probability Analysis Input

Card AA: The statistics are determined on the basis of 100 samplings of factor of safety. The random number seed is 3., and a maximum detail output is requested. The ideogram plot has a width of 50 columns across the page, and each class on the plot spans an interval of 0.02. The critical factor of safety is 1., and the soil profile lines, material values and pressure/piezometric values are sampled.

Card BB: The thickness of the middle soil layer is uncertain so the third soil profile line is sampled. All points on that line are varied by the same amount in the y-direction only. The probability distribution curve is triangular, and the y-values can be as small as 50 ft (15.2 m) less than the average value and as large as 20 ft (6.1 m) greater than the average value.

Card CC: The  $c$ ,  $\phi$ , and  $\gamma$  values of the material are sampled. In specifying the distributions, care must be taken to ensure that these values do not fall below zero during sampling. In most of these cases

a simple gaussian distribution is sufficient to satisfy this restriction - the sampled value may be as much as six standard deviations either side of the mean. For  $\phi$  of Material Type 2, it is necessary, however, to use the truncated gaussian distribution to confine the sampled value to a positive number.

Card DD: The shape of the piezometric line within the slope is not well-defined, so one point on this line is sampled with a uniform distribution in the y-direction only.

163. The results of this analysis are included in Exhibit D-3.

164. The first part of the output corresponds to the basic analysis in which the specified average values are taken to be deterministic. The printout shows these average values, and this is followed by slice information, iteration information and solution information. The iteration information shows that the convergence was achieved in four iterations. The factor of safety is given as 0.888.

165. The deterministic analysis is always performed when the probabilistic analysis is requested. If this first part is not successfully executed, the probabilistic analysis is not carried out, and the program execution is automatically terminated.

166. Next, there comes the printout of the input for the probabilistic analysis under the heading PROBABILITY INPUT DATA. This shows, eg, that 100 analyses were performed, based on the sample size of 100.

167. The SOIL PROFILE LINE INPUT DATA shows that Soil Profile Line 3 was taken to be uncertain, implying that the thickness of the rock layer immediately below the alluvium was uncertain. The two points defining the line were to be sampled together in the y-direction using a triangular distribution with  $ST1 = 50$  ft (15.2 m) and  $ST2 = 20$  ft (6.1 m). The rock layer immediately below the alluvium could then be  $150 + 50 = 200$  ft (61.0 m) thick at one extreme and  $150 - 20 = 130$  ft (39.6 m) at the other.

168. The MATERIAL INPUT DATA shows that the

properties defined for all three material types are normally distributed, but for the friction angle of Material Type 2, ie, profile 2, the lower bound is at  $0^\circ$  and the upper bound is at  $65^\circ$ .

169. The piezometric line is shown to be uncertain, as described earlier.

170. The list of input is followed by the results under the heading DETAIL OF ANALYSIS as requested. This lists the values which were sampled for the statistical variables, together with the computed factor of safety, side force inclination, and force and moment imbalance corresponding to the specified input. For example, for SAMPLE NUMBER = 1 the factor of safety = 0.92, the side force inclination =  $-30.56^\circ$ , the number of iterations = 4, and the moment and force imbalance = 0.00. The information is repeated for the entire sample size, which would be 100, if the detail print option is used as in this example. In Exhibit D-3, the details

corresponding to sample numbers 4 through 97 are omitted to save space.

171. The detail is followed by a table of calculated values of the factor of safety, including the maximum and minimum.

172. Finally, the frequency distribution of the factor of safety is plotted against the user-controlled class interval; in this example a step size of 0.02 was chosen. The mean (0.879), standard deviation (0.079), skewness (0.053), kurtosis (2.69), and sample size (100) are listed under SAMPLE STATISTICS. The probability of instability, assuming that the distribution is normal with mean = sample mean and standard deviation = sample standard deviation is given as 93.77%. By direct count the probability of instability is 92%.

#### FLOW CHART

173. A macro-flow chart is shown in Fig D-13.



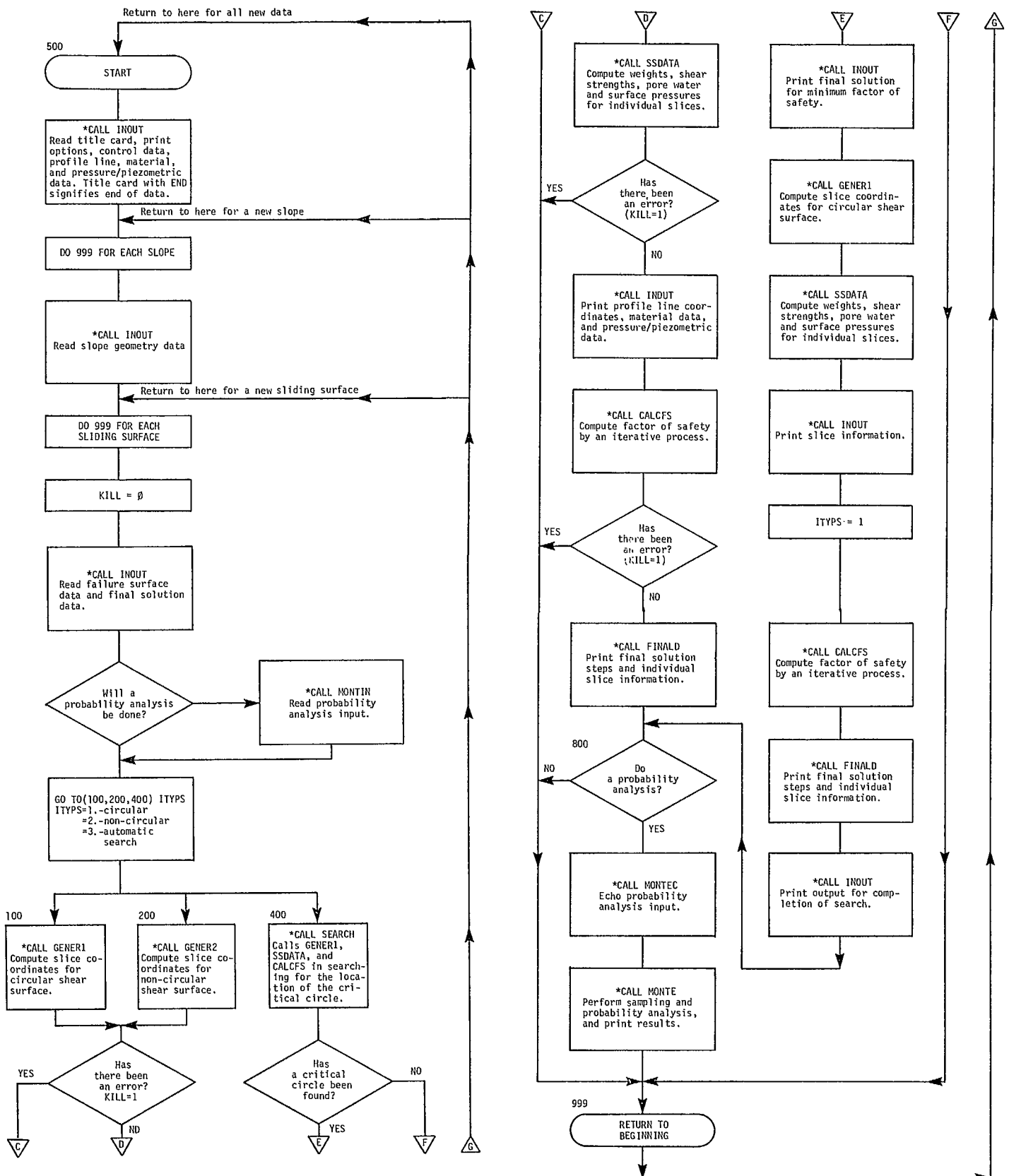


Fig D-13 - Flow chart for GENSAM.

## SYSTEM DOCUMENTATION

### COMPUTER EQUIPMENT

174. CDC 6400.

### PERIPHERAL EQUIPMENT

175. Line printer and card reader.

### SOURCE PROGRAM

176. A source deck and listing can be obtained from: Mining Research Laboratories, CANMET, 555 Booth Street, Ottawa, Ontario, K1A 0G1, Canada.

### MAIN PROGRAM AND SUBROUTINES

Main Program GENSAM is used mainly to call other supporting subroutines. The subroutines described below are not in the order called.

INOUT - reads input data and prints the input and output information.

IOFLAG - prints error messages for input data.

ETIME - computes elapsed time.

GENER1 - computes slice coordinates for circular shear surfaces.

INTSCT - computes the intersections of the circle with soil geometry lines.

GENER2 - computes slice coordinates for noncircular shear surfaces.

PIEZEL - computes the piezometric elevation above the centre of the base of each slice.

INTERP - interpolates appropriate values of pore pressure or  $r_u$  at the centre of the base of each slice.

SSDATA - computes weights, shear strengths, pore pressures, and surface pressures for individual slices.

SLAE1 - solves simultaneous linear algebraic

equations.

CALCFS - calculates the factor of safety.

FINALD - computes and prints the final solution information for individual slices.

GRID - sets up grid array used for search.

SEARCH - searches for location of critical circle.

EFLAG - prints computation error messages.

MONTIN - reads control data, values to be sampled, and distributions for the probability analysis.

MONTEC - prints data read in by subroutine MONTIN.

MONTE - calculates factor of safety from sampled profile line, material, and pressure/piezometric values. This is done as many times as specified, and the resulting factors of safety are analyzed statistically and shown on a printer plot.

LINKER - sets up a table which identifies points in the profile line data that have identical (X,Y) values.

SOLSAM - samples soil profile points based on user input.

PRESAM - samples pressure and piezometric points based on user input.

### DATA STRUCTURES

177. No special data structures are used.

### STORAGE REQUIREMENTS

178. 102000 octal on the CDC 6600.

### MAINTENANCE AND UPDATES

179. None.

## OPERATING DOCUMENTATION

### OPERATING INSTRUCTIONS

180. There are no special operating instructions for this program.

### CONTROL CARDS

181. Control cards used are standard CDC control cards for loading and executing a program.

### ERROR RECOVERY

182. Program must be restarted on error.

### RUN TIME

183. The execution time and cost depends on the size of problem and the option used for analysis. The sample run was executed in approximately 30 seconds on a CDC 6600 and cost \$8.50.



EXHIBIT D-1

PROGRAM GENSAM

SPENCER AND WRIGHT STABILITY ANALYSIS

DESCRIPTION OF INPUT VARIABLES



This description of variables is to be used in conjunction with the Input Data Sheet which follows.

#### A. HEADER DATA

JOBNO - Job number  
 INI - Engineer's initials, three letters, 3 columns  
 IDATE - Date, MMDDYY, month, day and year, 6 columns  
 IHEAD - Any descriptive identifier, up to 59 columns

#### B. OUTPUT CONTROL DATA

ISUP = 0. - print input data  
 = 1. - input data are not printed  
 ISUP1 = 0. - print information on each circle of an automatic search, ITYP=3., is not printed  
 ISUP2 = 0. - print individual slice information  
 = 1. - slice information is not printed

#### C. SOIL PROFILE DATA

NP = total number of profile lines, Max=20  
 NMATS = number of material types in soil profile, Max=20  
 MBPL1 = 0. - no surface pressure specified  
 = NMATS+1 - surface pressure specified  
 MBPL2 = 0. - no surface pressure or no discontinuity exists in surface pressures  
 = NMATS+2 - discontinuity exists in surface pressures  
 NPIEZ = 0. - no piezometric line is specified  
 = NMATS+1 - no surface pressure specified  
 = NMATS+2 - surface pressure specified but MBPL2 = 0.

= NMATS+3 - surface pressure specified and MBPL2 = NMATS + 2

UWW = unit weight of water; if blank, default = 62.4 lb/cu ft

KEEP1 = 0. - soil profile lines are changed or defined for first analysis  
 = 1. - soil profile line data from previous analysis to be used. Omit D and E data lines

KEEP2 = 0. - material data changed or defined for first analysis  
 = 1. - material (soil) data from previous analysis to be used. Omit F data line

KEEP3 = 0. - pressure data changed or defined for first analysis  
 = 1. - pressure data from previous analysis to be used. Omit G and H data lines

#### D. PROFILE LINE CONTROL DATA

NPP - total number of coordinates specified for first profile line; Max=15  
 MATYPE - identification number of the material type used with the profile line. Number from the range 1 through NMATS.

#### E. PROFILE LINE COORDINATE DATA POINTS

XP - x-coordinate of profile line data point  
 YP - y-coordinate of profile line data point

#### F. MATERIAL DATA

##### OPTIONS:

##### 1. STANDARD C, $\phi$ STRENGTH CHARACTERIZATION (TYPE I PROFILE LINES)

C - cohesion, psf  
 CUPONZ - BLANK  
 REFHT - BLANK

- PHI - angle of internal friction, degrees  
 GAMMA - unit weight of soil ( $\gamma$  soil) below profile line  
 RU - constant pore water pressure,  $u$ , or pore water pressure ratio,  $r_u$ , for KODEP = 1. or 2.  
 KODEP - code for specification of pore water pressure  
     = 0. - no  $u$   
     = 1. - constant  $u$   
     = 2. - constant  $r_u$   
     = 3. -  $u$  obtained by interpolation from values of  $u$  at various points  
     = 4. -  $r_u$  obtained by interpolation from value of  $r_u$  at various points  
     = 5. - pressure defined by piezometric lines  
 KEY - BLANK  
 KEY - BLANK
2.  $\phi = 0$  STRENGTH ENVELOPE, SHEAR STRENGTH INCREASING LINEARLY WITH DEPTH BELOW A HORIZONTAL DATUM (TYPE I PROFILE LINES)
- C - undrained shear strength at the elevation of the horizontal datum, psf  
 CUPONZ - rate of increase of C with depth, psf/ft dept; positive value when strengths increase with depth  
 REFHT - reference elevation, specified as a y coordinate of the horizontal datum  
 PHI - BLANK  
 GAMMA - unit weight of soil ( $\gamma$  soil) below profile line  
 RU - BLANK  
 KODEP - BLANK  
 KEY - BLANK  
 KI - BLANK
3. ANISOTROPIC SHEAR STRENGTHS (TYPE I PROFILE LINES)
- C - values of C for a  $-90^\circ$  degree failure plane orientation, psf  
 CUPONZ - BLANK
- REFHT - BLANK  
 PHI - BLANK  
 GAMMA - unit weight of soil below profile line  
 RU - BLANK  
 KODEP - BLANK  
 KEY = 1. - for anisotropic shear strengths  
 KI - BLANK
- The values for C and CUPONZ of the remaining failure plane orientations,  $-80$  to  $+90$  degrees, should appear on the following four cards in pairs across the cards in fields of eight columns. All values for CUPONZ should be left blank for this type of soil description ie,
- CARD 1 - COL. 1 - C for  $-80^\circ$   
           COL. 9 - BLANK  
           COL. 17 - C for  $-70^\circ$   
           COL. 25 - BLANK  
           COL. 33 - C for  $-60^\circ$   
           etc.
4. ANISOTROPIC SHEAR STRENGTHS INCREASING LINEARLY WITH DEPTH (TYPE I PROFILE LINES)
- C - value of C for a  $-90^\circ$  degree failure plane orientation at the elevation of the horizontal datum, psf  
 CUPONZ - rate of increase in C with depth for a  $-90^\circ$  degree orientation of the failure plane, psf/ft depth. Positive value when strength increases with depth.  
 REFHT - reference elevation, specified as a y coordinate of the horizontal datum  
 PHI - BLANK  
 GAMMA - unit weight of soil ( $\gamma$  soil) below profile line  
 RU - BLANK  
 KODEP - BLANK  
 KEY - 1. - for anisotropic shear strengths  
 KI - BLANK
- The values for C and CUPONZ of the remaining failure plane orientations,  $-80$  to  $+90$



degrees, should appear on the following four cards in pairs across the cards in fields of eight columns ie,

CARD 1 - COL. 1 - C for  $-80^\circ$   
 COL. 9 - CUPONZ for  $-80^\circ$   
 COL. 17 - C for  $-70^\circ$   
 COL. 25 - CUPONZ for  $-70^\circ$   
 COL. 33 - C for  $-60^\circ$   
 etc.

#### 5. STRENGTH ALONG SOIL PROFILE (CONTOUR) LINES (TYPE II PROFILE LINES)

C - values of the undrained shear strength along the soil profile line, psf

CUPONZ - BLANK

REFHT - BLANK

PHI - BLANK

GAMMA - unit weight of soil ( $\gamma$  soil) below profile line

RU - BLANK

KODEP - BLANK

KEY - 2. - indicates data correspond to Type II profile line

KI - any positive, nonzero integer; the values of this integer must be identical for all material types and corresponding profile lines within the same soil stratum as in Note 1

OMIT DATA LINES G AND H IF NO PRESSURE DATA ARE SPECIFIED

#### G. NUMBER OF PRESSURE DATA POINTS

NPDATA - total number of data points for  $u$  or  $r_u$  interpolation, surface pressure loading and piezometric line. Max=300

#### H. PRESSURE DATA

Omit subgroup data lines H when no pressure data are specified. Data for each subgroup must be specified before continuing to next subgroup.

##### 1. PORE WATER PRESSURE

XPP - x-coordinate of point at which  $u$  or  $r_u$  is specified

YPP - y-coordinate of point at which  $u$  or  $r_u$  is specified

PP - value of pore water pressure of  $r_u$

MTYPE - the number of the material type to which the above data pertain

#### 2. SURFACE PRESSURE

XPP - x-coordinate of the applied pressure point

YPP - y-coordinate of the applied pressure point

PP - Value of pressure normal to the slope and ground surface

MTYPE - MBPL1 or MBPL2 See data input line C above)

#### 3. PIEZOMETRIC LINE

XPP - x-coordinate of a point on piezometric line from left to right

YPP - y-coordinate of a point on piezometric line from left to right

PP - BLANK

MTYPE - NPIEZ (see data line C above)

#### I. TOTAL NUMBER OF SLOPES TO BE ANALYZED

NSLOPS - total number of slopes to be analyzed for the specified soil profile; no limit

#### J. SLOPE TITLE

STITLE - Any descriptive title for the slope which will be printed as an output heading

#### K. NUMBER OF SLOPE COORDINATES

NSP - Total number of slope coordinate points; Max=20

KEEP4 = 0. - new coordinates are supplied first time or changed

= 1. - previous analysis coordinate data are to be used; omit data card/line L, but specify NSP again on this data line (see Note 2)

#### L. SLOPE COORDINATE DATA POINTS

XS - x-coordinate of slope or ground surface point from left to right

YS - y-coordinate of slope or ground surface point from left to right

#### M. NUMBER OF ANALYSES

NSTART - total number of individually selected shear surfaces to be analyzed (ITYPS = 1. or 2. on card/line N), and independently started searches to be performed (ITYPS = 3.)

#### N. ANALYSIS OPTION DATA

ITYPS = 1. - single, individually selected, circular shear surface is to be analyzed  
 = 2. - single, individually selected, non-circular shear surface is to be analyzed  
 = 3. - automatic search is to be conducted to locate a critical circle

#### O. INDIVIDUAL CIRCLE DATA (ITYPS=1.)

##### 1. CARD 1

XC - x-coordinate of the centre of the circle  
 YC - y-coordinate of the centre of the circle  
 R - radius of the circle, ft  
 - 99999. if the circle is to pass through the specified point with the coordinates XFIX, YFIX eg, circle passing through toe of the slope  
 THETA - angle subtended by radii extended to each side of the base of a slice, degrees (see Note 3)  
 ARCMAX - arc length along the base of a slice (see Note 3)  
 XFIX - x-coordinate of the specified point through which the circle is assumed to pass  
 YFIX - y-coordinate of the specified point through which the circle is assumed to pass

##### 2. CARD 2

DTC - depth of tension crack below the surface of the slope  
 DWATER - depth of water above the base of the tension crack

#### P. NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

##### 1. CARD 1

NCORDS - total number of coordinates to be specified along the non-circular shear surface  
 DWATER - Depth of water above the base of the tension crack

##### 2. CARD 2

X - Coordinate of the points on the shear failure surface. 5 (x,y) points on one data line  
 Y - Coordinate of the points on the shear failure surface. 5 (x,y) points on one data line

#### Q. AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

##### 1. CARD 1

XG - x-coordinate of the centre of the circle, initial  
 YG - y-coordinate of the centre of the circle, initial  
 ROCKLN - y-coordinate specifying the elevation of the hypothetical, horizontal rockline used for initial mode of search  
 - Blank if ICIRCLE = 2. in next data line  
 XFIX - x-coordinate of the specified point through which all circles are assumed to pass for initial mode of search  
 - Blank if ICIRCLE = 1. in next data line  
 YFIX - y-coordinate of the specified point through which all circles are assumed to pass for initial mode of search  
 - blank, if ICIRCLE = 1. in next line  
 ROCK - y-coordinate of the limiting

elevation, below which the critical circle is not permitted to pass

- ACC - required accuracy in the location of the coordinates for the centre of critical circle; this value determines the minimum grid spacing which will be used in automatic search
- TIMEL - maximum time in seconds allowed for locating the critical circle; if blank, default = 120.

## 2. CARD 2

- ICIRCL = 1. - all circles are tangent to a hypothetical, horizontal rockline
- = 2. - all circles pass through a fixed point
- THETA - angle subtended by radii extended to each side of the base of a slice, deg
- ARCMAX - arc length along the base of a slice, ft
- DTC - depth of assumed tension crack below the surface of the slope, ft
- DWATER - depth of water above the base of tension crack, ft

## R. SOLUTION DATA

- FZ - initial assumed value for the factor of safety; if blank,

default = 2.

- THETAZ - initial assumed value for the side force inclination, degrees; if less than  $-40^\circ$  or greater than  $+40^\circ$ , the program assumes a value of  $0^\circ$  for the initial value
- FLIMIT - allowed force imbalance for static equilibrium, lb; default value 100 lb or any other consistent units
- TLIMIT - allowed moment imbalance for static equilibrium; if zero or negative, a default value = 100 ft-lb or any other consistent units
- ITERL - maximum number of iterations allowed for computing the factor of safety; if not in range of 5 to 40, a value of 20 is assumed. (see Note 4)
- MONT = 0. - no probability input data
- = 1. - read new probability data; Card AA must follow card R
- = 2. - do probability analysis using all previous probability data

## S. END CONTROL DATA

- END - code to indicate termination of input data; the word END must be entered in first three columns. (see Notes 5 and 6)

## DESCRIPTION OF INPUT VARIABLES FOR THE PROBABILITY ANALYSIS

### AA. CONTROL DATA

NSAMPL - number of factors of safety to be calculated and analyzed

MF - random number seed, must be a real representation of an odd, positive, integer.

MPRT = 0. - print input values and results of statistical analysis of factors of safety

= 1. - Option 0. plus factor of safety table

= 2. - Option 1. plus number of iterations and side force inclination for each sample

= 3. - Option 2. plus printout of all sampled values which were used in factor of safety calculation, force imbalance, and moment imbalance.

NX - width of ideogram across the computer page; Max = 100

BINSIZ = 1. - size of each class for ideogram

= 1. - number of classes in ideogram

FC - value of factor of safety below which slope is assumed to fail

ISOIL = 0. - no soil profile values to be sampled

= 1. - read soil profile data

= 2. - sample soil profile values according to data read in the previous analysis

IMATR = 0. - no material values to be sampled

= 1. - read material data

= 2. - sample material values according to data read in the previous analysis

IPRES = 0. - no pressure or piezometric values to be sampled

= 1. - read pressure and/or piezometric data

= 2. - sample pressure and/or piezometric values according to data read in the previous analysis

### BB. SOIL GEOMETRY DATA

IASOL - soil line number to be sampled; lines are numbered in the order in which they were originally

input into the program;  
 if IASOL is given as a positive value, all points to be sampled on this line will change by the same amount in the same direction ie, the first point is sampled, a delta value is calculated, and this value is applied to all the other points;  
 if a minus sign precedes the line number, all points specified will be sampled independently

IBSOL - number of points to be sampled on the specified line if this value equals 0. all points on the line will be sampled  
 ICSOL = 0. - sample X and Y values  
 = 1. - sample X values only  
 = 2. - sample Y values only  
 SDIST - distribution type code  
 SST1 - ST1  
 SST2 - ST2  
 SST3 - ST3

Descriptions of distribution type codes are found in para 131-133.

NPTSOL - only to be used when IBSOL  $\neq$  0.; these are point numbers which are to be sampled within the soil line; three point numbers can be placed in fields 8, 9 and 10 of the first card, and thereafter 10 points on each successive card, up to a maximum of 15 points.

#### CC. MATERIAL DATA

I - material type to be sampled; types are numbered in the order which they were input into the program  
 J - variable number code to be sampled  
 1. = C, for material types 3 and 4, all 19 C values are varied with the same increment

2. = CUPONZ, for material type 4, all 19 CUPONZ values are varied with the same increment  
 3. = REFHT  
 4. = PHI  
 5. = GAMMA  
 6. = RU

MDIST - distribution type code  
 MST1 - ST1  
 MST2 - ST2  
 MST3 - ST3

Descriptions of distribution type codes are found in para 131-133.

#### DD. PRESSURE AND PIEZOMETRIC DATA

IAPRE - Type (MTYPE) of data to be sampled  
 = 1 to NMATS - pore pressure  
 = MBPL1 or MBPL2 - surface pressure  
 = NPIEZ - Piezometric line when  $1 \leq |IAPRE| \leq MBPL2$ , the pressure values are sampled rather than the points at which they are applied; in these cases ICPRE as shown below, will always be 0.  
 When  $|IAPRE| = NPIEZ$ , the points at which the piezometric line is defined are sampled (x and/or y values depending on ICPRE).  
 This variable may be plus or minus depending on whether the points or values are to be sampled together or independently (see IASOL, card BB)

IBPRE - Number of points to be sampled within particular MTYPE. If this value equals 0. all of that particular MTYPE will be sampled  
 ICPRE - Relevant only when  $|IAPRE| = NPIEZ$   
 = 0. - Sample X and Y values  
 = 1. - Sample X values only  
 = 2. - Sample Y values only  
 PDIST - distribution type code  
 PST1 - ST1

PST2 - ST2  
PST3 - ST3

Distribution type codes are described in para 131-133.

NPTPRE - Only to be used when IBPRE  $\neq$  0.  
These are point numbers which are to be sampled within MTYPE.  
Points in this case are not

numbered from the beginning of all the pressure/piezometric data but rather from the beginning of each different MTYPE, see para 129. Three point numbers can be placed in fields 8, 9, and 10 of the first card, and thereafter 10 points on each successive card, to a maximum of 30 points.

## NOTES

### Note 1

This code, KI, is specified with the material data for each profile line and provides the means for identifying all Type II profile lines which lie within a particular soil stratum, the values of code being identical for all profile lines within each stratum.

### Note 2

The use of this code, KEEP4, is applicable only when new soil profile or pressure data have been given on data card/line B through H -- not applicable for several shear surfaces with the same slope because this is controlled by the value of NSTART on data card/line M.

### Note 3

A value of either the angle, THETA, or the arc length, ARCMAX, must be specified for subdividing the circle into slices. The rest of these values must be left blank.

### Note 4

- a. Repeat data lines N through R, as required, for additional shear surfaces, and search with new starting modes.
- b. Repeat data lines J through R as required, for additional analysis with new slope geometry, but using the same soil profile data, including material properties, pore water, and surface pressures.

- c. Repeat data lines A through R, as required, for additional analysis with new soil profile data.

### Note 5

- a. The word "data line" in the input data sheet means that data is to be punched onto one card.
- b. The units of data must be consistent; ie, FPS, foot, pound, second, MKS, meter, kilogram, second, SI, International System. The computer printed output will however, be labelled in units of feet and pounds.

### Note 6

- a. Sign Conversion: The angle of inclination of the side forces is referenced to a horizontal plane and positive values are measured in a clockwise direction. The force inclination will normally be positive for a right facing slope and negative for a left facing slope.
- b. Profile Lines: The total number of profile lines refers to the number of continuous profile lines, not to the total number of shorter straight line segments.
- c. Shear Surface: Care must be taken to ensure that the last two coordinate points at either end of the shear surface are not both above the slope.
- d. Variable names used in input data sheet correspond to the FORTRAN variable names in the computer program.





[illegible]

## F. MATERIAL DATA

[illegible]

NPDATA

[illegible][illegible]

NSLOPS

PAGE 5

STITLE	
I	

NSP                      KEEP4

XS	YS	XS	YS	XS	YS	XS	YS	XS	YS
<hr/>									
<hr/>									
<hr/>									
<hr/>									

```

NSTART
|      |

```

## N. ANALYSIS OPTION DATA

ITYPS  
|  
-----

## O. INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCMAX	XFIX	YFIX
DTC	DWATER					

## P. NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCORDS		DWATER							
X	Y	X	Y	X	Y	X	Y	X	Y

## Q. AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XG	YG	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL
ICIRCL	THETA	ARCMAX	DTC	DWATER			

## R. SOLUTION DATA

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT

MONT=1. - INPUT CONTINUES ON NEXT 2 PAGES

MDNT=0. OR 2. - RETURN TO LINE N FOR EACH ANALYSIS (TO NSTART)  
 RETURN TO LINE J FOR EACH SLOPE (TO NSLOPS)  
 RETURN TO LINE A FOR NEW ANALYSIS

## S. END CONTROL DATA

END  
|  
-----

AA.

NSAMPL	MF	MPRT	NX	BINSIZ	FC	ISOIL	IMATR	IPRES
1								

BB.

[illegible]

PAGE 9

I	J	MDIST	MST1	MST2	MST3
1	1	1	1	1	1
1	2	1	1	1	1
1	3	1	1	1	1
1	4	1	1	1	1
1	5	1	1	1	1
1	6	1	1	1	1
1	7	1	1	1	1
1	8	1	1	1	1
1	9	1	1	1	1
1	10	1	1	1	1
2	1	1	1	1	1
2	2	1	1	1	1
2	3	1	1	1	1
2	4	1	1	1	1
2	5	1	1	1	1
2	6	1	1	1	1
2	7	1	1	1	1
2	8	1	1	1	1
2	9	1	1	1	1
2	10	1	1	1	1
3	1	1	1	1	1
3	2	1	1	1	1
3	3	1	1	1	1
3	4	1	1	1	1
3	5	1	1	1	1
3	6	1	1	1	1
3	7	1	1	1	1
3	8	1	1	1	1
3	9	1	1	1	1
3	10	1	1	1	1
4	1	1	1	1	1
4	2	1	1	1	1
4	3	1	1	1	1
4	4	1	1	1	1
4	5	1	1	1	1
4	6	1	1	1	1
4	7	1	1	1	1
4	8	1	1	1	1
4	9	1	1	1	1
4	10	1	1	1	1
5	1	1	1	1	1
5	2	1	1	1	1
5	3	1	1	1	1
5	4	1	1	1	1
5	5	1	1	1	1
5	6	1	1	1	1
5	7	1	1	1	1
5	8	1	1	1	1
5	9	1	1	1	1
5	10	1	1	1	1
6	1	1	1	1	1
6	2	1	1	1	1
6	3	1	1	1	1
6	4	1	1	1	1
6	5	1	1	1	1
6	6	1	1	1	1
6	7	1	1	1	1
6	8	1	1	1	1
6	9	1	1	1	1
6	10	1	1	1	1
7	1	1	1	1	1
7	2	1	1	1	1
7	3	1	1	1	1
7	4	1	1	1	1
7	5	1	1	1	1
7	6	1	1	1	1
7	7	1	1	1	1
7	8	1	1	1	1
7	9	1	1	1	1
7	10	1	1	1	1
8	1	1	1	1	1
8	2	1	1	1	1
8	3	1	1	1	1
8	4	1	1	1	1
8	5	1	1	1	1
8	6	1	1	1	1
8	7	1	1	1	1
8	8	1	1	1	1
8	9	1	1	1	1
8	10	1	1	1	1
9	1	1	1	1	1
9	2	1	1	1	1
9	3	1	1	1	1
9	4	1	1	1	1
9	5	1	1	1	1
9	6	1	1	1	1
9	7	1	1	1	1
9	8	1	1	1	1
9	9	1	1	1	1
9	10	1	1	1	1
10	1	1	1	1	1
10	2	1	1	1	1
10	3	1	1	1	1
10	4	1	1	1	1
10	5	1	1	1	1
10	6	1	1	1	1
10	7	1	1	1	1
10	8	1	1	1	1

DD. PRESSURE AND PIEZOMETRIC DATA

[illegible]

BLANK CARD TERMINATES THIS DATA SET

EXHIBIT D-2

LOAD SHEETS, LIST OF INPUT DATA  
AND OUTPUT FOR DETERMINISTIC CASE

INPUT DATA

OUTPUT



```
=====
=              PROGRAM GENSAM              =
= SPENCER AND WRIGHT SLOPE STABILITY ANALYSIS =
=              INPUT DATA SHEET          =
=====
```

NOTES: 1. ALL CARDS EXCEPT A AND J HAVE 8 COLUMNS/FIELD AND UP TO 10 FIELDS/CARD BEGINNING IN COLUMNS 1, 9, 17, 25, 33, 41, 49, 57, 65, AND 73. THE FIELDS IN CARD A BEGIN IN COLUMNS 1, 11, 14, AND 21. CARD J CONTAINS ONLY 1 FIELD WHICH BEGINS IN COLUMN 1.

2. ALL NUMERIC VALUES EXCEPT JOBND AND IDATE MUST CONTAIN A DECIMAL POINT.

JOBNO INI IDATE IHEAD  
10999999996.55123761 EXAMPLE PROG A - SCLF PROFILE No. 1

ISUP            ISUP1            ISUP2            | leave blank card

NP	NHATS	MBPL1	MBPL2	NPIEZ	UWW	KEEP1	KEEP2	KEEP3
13.	11.	13.	13.	14.	0.	0.	0.	0.

NPP	MATYPE
1 3.	1 /.

[illegible]

PAGE 2

REPEAT OF LINES D AND E FOR ADDITIONAL PROFILE LINES

NPP	MATYPE
3.	3.
XP	YP
385.	350.
XP	YP
405.	400.
XP	YP
415.	400.
XP	YP
425.	400.
XP	YP
435.	400.
XP	YP
445.	400.
XP	YP
455.	400.
XP	YP
465.	400.
XP	YP
475.	400.
XP	YP
485.	400.
XP	YP
495.	400.
XP	YP
505.	400.
XP	YP
515.	400.
XP	YP
525.	400.
XP	YP
535.	400.
XP	YP
545.	400.
XP	YP
555.	400.
XP	YP
565.	400.
XP	YP
575.	400.
XP	YP
585.	400.
XP	YP
595.	400.
XP	YP
605.	400.
XP	YP
615.	400.
XP	YP
625.	400.
XP	YP
635.	400.
XP	YP
645.	400.
XP	YP
655.	400.
XP	YP
665.	400.
XP	YP
675.	400.
XP	YP
685.	400.
XP	YP
695.	400.
XP	YP
705.	400.
XP	YP
715.	400.
XP	YP
725.	400.
XP	YP
735.	400.
XP	YP
745.	400.
XP	YP
755.	400.
XP	YP
765.	400.
XP	YP
775.	400.
XP	YP
785.	400.
XP	YP
795.	400.
XP	YP
805.	400.
XP	YP
815.	400.
XP	YP
825.	400.
XP	YP
835.	400.
XP	YP
845.	400.
XP	YP
855.	400.
XP	YP
865.	400.
XP	YP
875.	400.
XP	YP
885.	400.
XP	YP
895.	400.
XP	YP
905.	400.
XP	YP
915.	400.
XP	YP
925.	400.
XP	YP
935.	400.
XP	YP
945.	400.
XP	YP
955.	400.
XP	YP
965.	400.
XP	YP
975.	400.
XP	YP
985.	400.
XP	YP
995.	400.
XP	YP
1005.	400.
XP	YP
1015.	400.
XP	YP
1025.	400.
XP	YP
1035.	400.
XP	YP
1045.	400.
XP	YP
1055.	400.
XP	YP
1065.	400.
XP	YP
1075.	400.
XP	YP
1085.	400.
XP	YP
1095.	400.
XP	YP
1105.	400.
XP	YP
1115.	400.
XP	YP
1125.	400.
XP	YP
1135.	400.
XP	YP
1145.	400.
XP	YP
1155.	400.
XP	YP
1165.	400.
XP	YP
1175.	400.
XP	YP
1185.	400.
XP	YP
1195.	400.
XP	YP
1205.	400.
XP	YP
1215.	400.
XP	YP
1225.	400.
XP	YP
1235.	400.
XP	YP
1245.	400.
XP	YP
1255.	400.
XP	YP
1265.	400.
XP	YP
1275.	400.
XP	YP
1285.	400.
XP	YP
1295.	400.
XP	YP
1305.	400.
XP	YP
1315.	400.
XP	YP
1325.	400.
XP	YP
1335.	400.
XP	YP
1345.	400.
XP	YP
1355.	400.
XP	YP
1365.	400.
XP	YP
1375.	400.
XP	YP
1385.	400.

[illegible]

REPEAT OF LINES D AND E FOR ADDITIONAL PROFILE LINES

[illegible]



[illegible]

G. NUMBER OF PRESSURE DATA POINTS

68.

XPP	YPP	PP	MTYPE
445.	400.	0.	4.
449.	370.	0.	4.
453.	340.	0.	4.
457.	310.	0.	4.
461.	280.	0.	4.
465.	250.	0.	4.
450.	400.	0.15	4.
500.	375.	0.15	4.
550.	350.	0.15	4.
600.	325.	0.15	4.
650.	308.33	0.15	4.
700.	291.67	0.15	4.
750.	275.	0.15	4.
825.	250.	0.15	4.

XPP	YPP	PP	MTYPE
750.	250.	0.15	4.
490.	335.	0.20	4.
525.	325.	0.20	4.
575.	305.	0.20	4.
625.	285.	0.20	4.
675.	270.	0.20	4.
710.	255.	0.20	4.
675.	250.	0.20	4.
625.	250.	0.20	4.
575.	250.	0.20	4.
535.	250.	0.20	4.
505.	265.	0.20	4.
490.	300.	0.20	4.
525.	245.	0.40	4.

111

## G. NUMBER OF PRESSURE DATA POINTS

NPDATA  

## H. PRESSURE DATA

XPP	YPP	PP	MTYPE
555.	290.	0.40	4.
595.	270.	0.40	4.
545.	270.	0.40	4.
0.	100.	18000.	6.
0.	125.	17000.	6.
75.	110.	17000.	6.
150.	115.	17000.	6.
0.	175.	14000.	6.
75.	165.	14000.	6.
160.	155.	14000.	6.
250.	145.	14000.	6.
350.	135.	14000.	6.
0.	235.	11000.	6.
100.	225.	10000.	6.

XPP	YPP	PP	MTYPE
200.	210.	10000.	6.
300.	195.	10000.	6.
410.	180.	10000.	6.
495.	170.	10000.	6.
575.	155.	10000.	6.
200.	225.	9000.	6.
300.	225.	8000.	6.
400.	225.	7000.	6.
500.	225.	6000.	6.
625.	210.	6000.	6.
750.	195.	6000.	6.
850.	185.	6000.	6.
675.	225.	7000.	6.
850.	225.	2000.	6.

## I. TOTAL NUMBER OF SLOPES TO BE ANALYSED

NSLOPS  

## G. NUMBER OF PRESSURE DATA POINTS

NPDATA  

## H. PRESSURE DATA

XPP	YPP	PP	MTYPE
1000.	200.	2000.	6.
1000.	225.	400.	6.
0.	250.	9048.	12.
100.	250.	9048.	12.
290.	245.	0.	12.
750.	275.	0.	13.
825.	250.	1560.	13.
1000.	250.	1560.	13.
0.	345.		14.
415.	345.		14.
435.	250.		14.
465.	250.		14.

XPP	YPP	PP	MTYPE

## I. TOTAL NUMBER OF SLOPES TO BE ANALYSED

NSLOPS  
1.

## J.SLOPE TITLE

STITLE  
 | *EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT* |

## K.NUMBER OF SLOPE COORDINATES

NSP      KEEP4  
 | *7.*    | *0.*    |

## L.SLOPE COORDINATE DATA POINTS

XS	YS	XS	YS	XS	YS	XS	YS	XS	YS
<i>0.</i>	<i>250.</i>	<i>100.</i>	<i>250.</i>	<i>400.</i>	<i>400.</i>	<i>450.</i>	<i>400.</i>	<i>600.</i>	<i>325.</i>
<i>825.</i>	<i>250.</i>	<i>1000.</i>	<i>250.</i>						

## M.NUMBER OF ANALYSES

NSTART  
 | *3.*    |

## N.ANALYSIS OPTION DATA

ITYPS  
 | *1.*    |

## O.INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCMA	XFIX	YFIX
<i>700.</i>	<i>500.</i>	<i>99999.</i>	<i>0.</i>	<i>25.</i>	<i>950.</i>	<i>250.</i>
DTC	OWATER					
<i>0.</i>	<i>0.</i>					

## P.NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCORDS		DWATER									
X	Y	X	Y	X	Y	X	Y	X	Y	X	Y

## Q.AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XC	YC	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL
ICIRCL	THETA	ARCMA	DTC	DWATER			

## R. SOLUTION DATA

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT
2.50	20.	100.	200.	30.	

MONT=1. - INPUT CONTINUES ON NEXT 2 PAGES

MONT=0, OR 2. - RETURN TO LINE N FOR EACH ANALYSIS (TO NSTART)  
 RETURN TO LINE J FOR EACH SLOPE (TO NSLOPS)  
 RETURN TO LINE A FOR NEW ANALYSIS

## S. END CONTROL DATA

END
-----

## N. ANALYSIS OPTION DATA

ITYPS
3.

## O. INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCMAX	XFIX	YFIX

DTC	DWATER

## P. NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCORDS		DWATER	

X	Y	X	Y	X	Y	X	Y	X	Y

## Q. AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XG	YG	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL
650.	450.	300.	0.	0.	50.	10.	90.

ICIRCL	THETA	ARCMAX	DTC	DWATER
1.	4.	0.	0.	0.

## R. SOLUTION DATA

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT
2.50	20.	100.	200.	20.	

MONT=1. - INPUT CONTINUES ON NEXT 2 PAGES

MONT=0. OR 2. - RETURN TO LINE N FOR EACH ANALYSIS (TO NSTART)  
 RETURN TO LINE J FOR EACH SLOPE (TO NSLOPS)  
 RETURN TO LINE A FOR NEW ANALYSIS

## S. END CONTROL DATA

END
-----

## N. ANALYSIS OPTION DATA

ITYPS
2.

## O. INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCMAX	XFIX	YFIX

DTC	DWATER

## P. NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCORDS		DWATER	
9.	0.		

X	Y	X	Y	X	Y	X	Y	X	Y
375.	337.5	475.	200.	500.	175.	525.	165.	550.	160.
575.	155.	600.	155.	800.	175.	950.	250.		

## Q. AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XG	YG	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL

ICIRCL	THETA	ARCMAX	DTC	DWATER

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT
1 2.50	1 20.	1 100.	1 200.	1 30.	1

END

```
=====
=                PROGRAM GENSAM                =
= SPENCER AND WRIGHT SLOPE STABILITY ANALYSIS =
=                INPUT DATA SHEET              =
=====
```

JOBNO      INI IOATE      IHEAO  
10999999999 05510317761 EXAMPLE PROB. A - SOIL PROFILE No. 3

ISUP            ISUP1            ISUP2            | leave blank card

NP	NMATS	MBPL1	MBPL2	NPIEZ	UWW	KEEP1	KEEP2	KEEP3
13.	11.	12.	13.	14.	0.	1.	0.	0.

```

Npp      MATYPE
|         |         |
-----

```

[illegible]

## F. MATERIAL DATA

[illegible]

PAGE 4

### G. NUMBER OF PRESSURE DATA POINTS

NPDATA  
1 10. 1

#### H. PRESSURE DATA

XPP	YPP	PP	MTYPE
0.	250.	9048.	12.
100.	250.	9048.	12.
390.	395.	0.	12.
750.	375.	0.	13.
825.	350.	1560.	13.
1000.	250.	1560.	13.
0.	375.		14.
414.33	395.		14.
750.	375.		14.
1000.	375.		14.

[illegible]

### I. TOTAL NUMBER OF SLOPES TO BE ANALYSED

NSLOPS  
| /t |

## N. ANALYSIS OPTION DATA

ITYPS  
1

## D. INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCHAX	XFIX	YFIX
DTC	DWATER					

## P. NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCONROS		DWATER	
X	Y	X	Y

## D. AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XG	YG	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL
0.50	4.75	0.	3.35	2.50	44.	10.	0.
ICIRCL	THETA	ARCHAX	DTC	DWATER			
2.	2.	0.	0.	0.			

## J. SLOPE TITLE

STITLE  
EXAMPLE Problem A - Earth Dam Embankment

## K. NUMBER OF SLOPE COORDINATES

NSP      KEEP4  
7      10

## L. SLOPE COORDINATE DATA POINTS

XS	YS	XS	YS	XS	YS	XS	YS	XS	YS

## M. NUMBER OF ANALYSES

NSTART  
10

## R. SOLUTION DATA

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT
2.50	20.	100.	200.	30.	

MONT=1. - INPUT CONTINUES ON NEXT 2 PAGES

MONT=0. OR 2. - RETURN TO LINE N FOR EACH ANALYSIS (TO NSTART)  
RETURN TO LINE J FOR EACH SLOPE (TO NSLOPS)  
RETURN TO LINE A FOR NEW ANALYSIS

## S. END CONTROL DATA

END  
END



## INPUT

0999999999GSS031776 EXAMPLE PROB. A - SOIL PROFILE NO. 1

13.	11.	12.	13.	14.	0.	0.	0.	0.
3.	1.							
100.	250.	400.	400.	405.	400.			
3.	2.							
385.	250.	405.	400.	415.	400.			
4.	3.							
395.	250.	415.	400.	435.	400.	455.	250.	
3.	2.							
435.	400.	445.	400.	465.	250.			
4.	4.							
445.	400.	450.	400.	600.	325.	825.	250.	
3.	5.							
0.	250.	395.	250.	410.	225.			
3.	5.							
440.	225.	455.	250.	1000.	250.			
2.	6.							
0.	225.	1000.	225.					
2.	7.							
0.	100.	1000.	200.					
2.	8.							
0.	90.	1000.	190.					
2.	9.							
0.	50.	1000.	100.					
2.	10.							
0.	0.	1000.	0.					
2.	11.							
0.	0.	1000.	0.					
0.	0.	0.	40.	135.	0.	5.	0.	0.
0.	0.	0.	35.	130.	0.	5.	0.	0.
800.	0.	0.	25.	120.	0.30	1.	0.	0.
500.	0.	0.	26.	123.	0.	4.	0.	0.
3200.	0.	0.	0.	120.	0.	0.	1.	0.
3200.		3120.		3040.		2880.		2680.
2440.		2120.		1800.		1600.		1600.
1680.		1840.		2080.		2400.		2800.
3200.		3480.		3600.				
350.	0.	0.	28.	115.	0.	3.	0.	0.
2000.	10.	200.	0.	125.	0.	0.	0.	0.
8000.	0.	0.	0.	126.	0.	0.	2.	9.
10000.	0.	0.	0.	126.	0.	0.	2.	9.
11000.	0.	0.	0.	126.	0.	0.	2.	9.
100000.	0.	0.	0.	150.	0.	0.	0.	0.

68.									
445.	400.	0.	4.						
449.	370.	0.	4.						
453.	340.	0.	4.						
457.	310.	0.	4.						
461.	280.	0.	4.						
465.	250.	0.	4.						
450.	400.	0.15	4.						
500.	375.	0.15	4.						
550.	350.	0.15	4.						
600.	325.	0.15	4.						
650.	308.33	0.15	4.						
700.	291.67	0.15	4.						
750.	275.	0.15	4.						
825.	250.	0.15	4.						
750.	250.	0.15	4.						
490.	335.	0.20	4.						
525.	325.	0.20	4.						
575.	305.	0.20	4.						
625.	285.	0.20	4.						
675.	270.	0.20	4.						
710.	255.	0.20	4.						
675.	250.	0.20	4.						
625.	250.	0.20	4.						
575.	250.	0.20	4.						
535.	250.	0.20	4.						
505.	265.	0.20	4.						
490.	300.	0.20	4.						
525.	295.	0.40	4.						
555.	290.	0.40	4.						
595.	270.	0.40	4.						
545.	270.	0.40	4.						
0.	100.	18000.	6.						
0.	125.	17000.	6.						
75.	120.	17000.	6.						
150.	115.	17000.	6.						
0.	175.	14000.	6.						
75.	165.	14000.	6.						
160.	155.	14000.	6.						
250.	145.	14000.	6.						
350.	135.	14000.	6.						
0.	225.	11000.	6.						
100.	225.	10000.	6.						
200.	210.	10000.	6.						
300.	195.	10000.	6.						
410.	180.	10000.	6.						
495.	170.	10000.	6.						
575.	155.	10000.	6.						
200.	225.	9000.	6.						
300.	225.	8000.	6.						
400.	225.	7000.	6.						
500.	225.	6000.	6.						
625.	210.	6000.	6.						
750.	195.	6000.	6.						
850.	165.	6000.	6.						
675.	225.	4000.	6.						
850.	225.	2000.	6.						
1000.	200.	2000.	6.						
1000.	225.	400.	6.						
0.	250.	9048.	12.						
100.	250.	9048.	12.						
390.	395.	0.	12.						
750.	275.	0.	13.						
825.	250.	1560.	13.						
1000.	250.	1560.	13.						
0.	395.		14.						
415.	395.		14.						
435.	250.		14.						
465.	250.		14.						
1.									
EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT									
7.	0.								
0.	250.	100.	250.	400.	400.	450.	400.	600.	325.
825.	250.	1000.	250.						
3.									
1.									
700.	500.	99999.	0.	25.	950.	250.			
0.	0.								
2.50	20.	100.	200.	30.					
3.									
650.	450.	200.	0.	0.	50.	10.	90.		
1.	4.	0.	0.						
2.50	20.	100.	200.	30.					
2.									
9.	0.								
375.	387.50	475.	200.	500.	175.	525.	165.	550.	160.
575.	155.	600.	155.	800.	175.	950.	250.		
2.50	20.	100.	200.	30.					

0999999999GSS031776 EXAMPLE PROB. A - SOIL PROFILE NO. 2

13.	11.	12.	13.	14.	0.	1.	0.	0.
0.	0.	0.	40.	135.	0.	5.	0.	0.
0.	0.	0.	35.	130.	0.	5.	0.	0.
800.	0.	0.	25.	120.	0.30	1.	0.	0.
500.	0.	0.	26.	123.	0.25	1.	0.	0.
2500.	0.	0.	0.	120.	0.	0.	0.	0.
350.	0.	0.	28.	115.	0.	5.	0.	0.
2000.	10.	200.	0.	125.	0.	0.	0.	0.
8000.	0.	0.	0.	126.	0.	0.	2.	9.
10000.	0.	0.	0.	126.	0.	0.	2.	9.
11000.	0.	0.	0.	126.	0.	0.	2.	9.
100000.	0.	0.	0.	150.	0.	0.	0.	0.
10.								
0.	250.	9048.	12.					
100.	250.	9048.	12.					
390.	395.	0.	12.					
750.	275.	0.	13.					
825.	250.	1560.	13.					
1000.	250.	1560.	13.					
0.	395.		14.					
414.33	395.		14.					
750.	275.		14.					
1000.	275.		14.					

1.  
EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

7.	1.						
1.							
3.							
650.	475.	0.	825.	250.	99.	10.	0.
2.	3.	0.	0.	0.			
2.50	20.	100.	200.	30.			

END

## OUTPUT

```

*****
*
*   PROGRAM GENSAM
*
*   SPENCER'S METHOD OF SLOPE STABILITY ANALYSIS
*
*   FOR GENERALIZED FAILURE SURFACES
*
*   LATEST REVISION - 3/ 1/76
*
*   DATE RUN - 21/03/77      TIME RUN - 16.32.41.
*
*****

```

```

0999999999 GSS 031776 EXAMPLE PROB. A - SOIL PROFILE NO. 1

```

PROFILE LINE NO.	MATERIAL TYPE	X	Y	COORDINATES X	COORDINATES Y	X	Y
1	1	100.00	250.00	400.00	400.00	405.00	430.00
2	2	385.00	250.00	405.00	400.00	415.00	400.00
3	3	395.00	250.00	415.00	400.00	435.00	400.00
4	2	435.00	400.00	445.00	400.00	465.00	250.00
5	4	445.00	400.00	450.00	400.00	600.00	325.00
6	5	0.00	250.00	395.00	250.00	410.00	225.00
7	5	440.00	225.00	455.00	250.00	1000.00	250.00
8	6	0.00	225.00	1000.00	225.00		
9	7	0.00	100.00	1000.00	200.00		
10	8	0.00	90.00	1000.00	190.00		
11	9	0.00	50.00	1000.00	100.00		
12	10	0.00	0.00	1000.00	0.00		
13	11	0.00	0.00	1000.00	0.00		

## M A T E R I A L   D A T A   -   T Y P E   1

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      0.00      0.00      0.00  
 PHI - - - - -                  40.00 DEGREES  
 UNIT WEIGHT - - - - -          135.00 PCF  
 PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE  
 UNIT WEIGHT OF WATER - - - - -  62.40 PCF

## M A T E R I A L   D A T A   -   T Y P E   2

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      0.00      0.00      0.00  
 PHI - - - - -                  35.00 DEGREES  
 UNIT WEIGHT - - - - -          130.00 PCF  
 PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE  
 UNIT WEIGHT OF WATER - - - - -  62.40 PCF

## M A T E R I A L   D A T A   -   T Y P E   3

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                     800.00      0.00      0.00  
 PHI - - - - -                  25.00 DEGREES  
 UNIT WEIGHT - - - - -          120.00 PCF  
 VALUE OF R-SUB-U - - - - -     .30

## M A T E R I A L   D A T A   -   T Y P E   4

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                     500.00      0.00      0.00  
 PHI - - - - -                  26.00 DEGREES  
 UNIT WEIGHT - - - - -          123.00 PCF  
 PORE PRESSURES INTERPOLATED FROM R-SUB-U DATA

## M A T E R I A L   D A T A   -   T Y P E   5

COHESION (UNDRAINED STRENGTH) - ANISOTROPIC  
   FAILURE PLANE          C          C/Z      REF. HT.  
 -90. DEGREES          3200.00      0.00      0.00  
 -80. DEGREES          3200.00     -0.00      0.00  
 -70. DEGREES          3120.00     -0.00      0.00  
 -60. DEGREES          3040.00     -0.00      0.00  
 -50. DEGREES          2880.00     -0.00      0.00  
 -40. DEGREES          2680.00     -0.00      0.00  
 -30. DEGREES          2440.00     -0.00      0.00  
 -20. DEGREES          2120.00     -0.00      0.00  
 -10. DEGREES          1800.00     -0.00      0.00  
    0. DEGREES          1600.00     -0.00      0.00  
   10. DEGREES          1600.00     -0.00      0.00  
   20. DEGREES          1680.00     -0.00      0.00  
   30. DEGREES          1840.00     -0.00      0.00  
   40. DEGREES          2080.00     -0.00      0.00  
   50. DEGREES          2400.00     -0.00      0.00  
   60. DEGREES          2800.00     -0.00      0.00  
   70. DEGREES          3200.00     -0.00      0.00  
   80. DEGREES          3480.00     -0.00      0.00  
   90. DEGREES          3600.00     -0.00      0.00  
 PHI - - - - -                  0.00 DEGREES  
 UNIT WEIGHT - - - - -          120.00 PCF  
 PORE PRESSURE - - - - -          0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   6

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                     350.00      0.00      0.00  
 PHI - - - - -                  28.00 DEGREES  
 UNIT WEIGHT - - - - -          115.00 PCF  
 PORE PRESSURES INTERPOLATED FROM PORE PRESSURE DATA

## M A T E R I A L   D A T A   -   T Y P E   7

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                     2000.00     10.00     200.00  
 PHI - - - - -                  0.00 DEGREES  
 UNIT WEIGHT - - - - -          125.00 PCF  
 PORE PRESSURE - - - - -          0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   8

COHESION (UNDRAINED STRENGTH)   -   ISOTROPIC  
    C            C/Z       REF. HT.  
    0.            8000.00    0.00       0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI =     9  
 PHI - - - - -     0.00 DEGREES  
 UNIT WEIGHT - - - - -     126.00 PCF  
 PORE PRESSURE - - - - -     0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   9

COHESION (UNDRAINED STRENGTH)   -   ISOTROPIC  
    C            C/Z       REF. HT.  
    0.            10000.00    0.00       0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI =     9  
 PHI - - - - -     0.00 DEGREES  
 UNIT WEIGHT - - - - -     126.00 PCF  
 PORE PRESSURE - - - - -     0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   10

COHESION (UNDRAINED STRENGTH)   -   ISOTROPIC  
    C            C/Z       REF. HT.  
    0.            11000.00    0.00       0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI =     9  
 PHI - - - - -     0.00 DEGREES  
 UNIT WEIGHT - - - - -     126.00 PCF  
 PORE PRESSURE - - - - -     0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   11

COHESION (UNDRAINED STRENGTH)   -   ISOTROPIC  
    C            C/Z       REF. HT.  
    0.            100000.00    0.00       0.00

PHI - - - - -     0.00 DEGREES  
 UNIT WEIGHT - - - - -     150.00 PCF  
 PORE PRESSURE - - - - -     0.00 PSF

PORE PRESSURE INTERPOLATION DATA				
	X	Y	U OF R(U)	MATERIAL TYPE
1	445.00	400.00	0.00	4
2	449.00	370.00	0.00	4
3	453.00	340.00	0.00	4
4	457.00	310.00	0.00	4
5	461.00	280.00	0.00	4
6	465.00	250.00	0.00	4
7	450.00	400.00	.15	4
8	500.00	375.00	.15	4
9	550.00	350.00	.15	4
10	600.00	325.00	.15	4
11	650.00	300.33	.15	4
12	700.00	291.67	.15	4
13	750.00	275.00	.15	4
14	825.00	250.00	.15	4
15	750.00	250.00	.15	4
16	490.00	335.00	.20	4
17	525.00	325.00	.20	4
18	575.00	305.00	.20	4
19	625.00	285.00	.20	4
20	675.00	270.00	.20	4
21	710.00	255.00	.20	4
22	675.00	250.00	.20	4
23	625.00	250.00	.20	4
24	575.00	250.00	.20	4
25	535.00	250.00	.20	4
26	505.00	265.00	.20	4
27	490.00	300.00	.20	4
28	525.00	295.00	.40	4
29	555.00	290.00	.40	4
30	595.00	270.00	.40	4
31	545.00	270.00	.40	4
32	0.00	100.00	18000.00	6
33	0.00	125.00	17000.00	6
34	75.00	120.00	17000.00	6
35	150.00	115.00	17000.00	6
36	0.00	175.00	14000.00	6
37	75.00	165.00	14000.00	6
38	160.00	155.00	14000.00	6
39	250.00	145.00	14000.00	6
40	350.00	135.00	14000.00	6
41	0.00	225.00	11000.00	6
42	100.00	225.00	10000.00	6
43	200.00	210.00	10000.00	6
44	300.00	195.00	10000.00	6
45	410.00	180.00	10000.00	6
46	495.00	170.00	10000.00	6
47	575.00	155.00	10000.00	6
48	200.00	225.00	9000.00	6
49	300.00	225.00	8000.00	6
50	400.00	225.00	7000.00	6
51	500.00	225.00	6000.00	6
52	625.00	210.00	6000.00	6
53	750.00	195.00	6000.00	6
54	850.00	185.00	6000.00	6
55	675.00	225.00	4000.00	6
56	850.00	225.00	2000.00	6
57	1000.00	200.00	2000.00	6
58	1000.00	225.00	400.00	6

SURFACE		PRESSURE		DATA	MTYPE
X	Y	Y	PRESSURE		(MBPL1 OR MEPL2)
1	0.00	250.00	9048.00		12
2	100.00	250.00	9048.00		12
3	390.00	395.00	0.00		12
4	750.00	275.00	0.00		13
5	825.00	250.00	1560.00		13
6	1000.00	250.00	1560.00		13

## PIEZOMETRIC ELEVATION DATA - NPIEZ = 14

	X	Y
1	0.00	395.00
2	415.00	395.00
3	435.00	250.00
4	465.00	250.00

## 1 SLOPE(S) ANALYZED FOR SOIL PROFILE TITLED -

0999999999 GSS 031776 EXAMPLE PROB. A - SOIL PROFILE NO. 1

KEEP1 = 0 KEEP2 = 0 KEEP3 = 0

## SLOPE DESIGNATION -

EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

## SLOPE POINTS

X	Y	X	Y	X	Y	X	Y	X	Y	X
0.00	250.00	100.00	250.00	400.00	400.00	450.00	400.00	600.00	325.00	825.00
1000.00	250.00									

## 3 SHEAR SURFACE(S) OR SEARCH(ES) CONSIDERED

EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

## C I R C L E D A T A

X COORDINATE OF CENTER	- - - - -	700.00 FT
Y COORDINATE OF CENTER	- - - - -	500.00 FT
RADIUS	- - - - -	353.55 FT
ALL CIRCLES PASS THROUGH THE FIXED POINT AT **	XFIX - -	950.00 FT
	YFIX - -	250.00 FT
CONSTANT ARC LENGTH SPECIFIED AS	- - - - -	25.00 FT
ASSUMED DEPTH OF TENSION CRACK	- - - - -	0.00 FT
ASSUMED DEPTH OF WATER IN TENSION CRACK	- - - - -	0.00 FT
UNIT WEIGHT OF WATER	- - - - -	62.40 PCF
INITIAL ASSUMED VALUE FOR FACTOR OF SAFETY	- - - - -	2.50
INITIAL ASSUMED VALUE FOR SIDE FORCE INCLINATION	- - - - -	20.00 DEGREES
ITERATION LIMIT	- - - - -	30
ALLOWED FORCE IMBALANCE SPECIFIED	- - - - -	100.00 LBS.
ALLOWED MOMENT IMBALANCE SPECIFIED	- - - - -	200.00 FT-LBS.

0.000 SECONDS REQUIRED IN GENER1

0.000 SECONDS REQUIRED IN SSDATA



## S L I C E I N F O R M A T I O N

NO.	X	Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES*
	LEFT CENTER RIGHT	LEFT CENTER RIGHT					AT SURFACE
							* FORCE-LOCATION*
							(LBS) X
	366.31	383.16					*
1	370.86	371.51	17073.	0.00	40.00	1465.48	* 6069. 370.50*
	375.40	359.87					*
2	380.20	349.66	52393.	0.00	40.00	2828.93	* 3281. 379.42*
	385.00	339.46					*
3	387.50	334.73	39839.	0.00	40.00	3760.90	* 436. 386.67*
	390.00	330.00					*
4	392.29	325.95	43460.	0.00	40.00	4308.82	* 0. 0.00*
	394.59	321.89					*
5	394.79	321.54	4236.	0.00	35.00	4583.87	* 0. 0.00*
	395.00	321.19					*
6	397.50	317.05	54478.	0.00	35.00	4863.91	* 0. 0.00*
	400.00	312.92					*
7	401.40	310.71	32882.	0.00	35.00	5259.67	* 0. 0.00*
	402.80	308.50					*
8	403.90	306.82	26520.	800.00	25.00	3616.75	* 0. 0.00*
	405.00	305.13					*
9	407.50	301.45	61944.	800.00	25.00	3716.65	* 0. 0.00*
	410.00	297.76					*
10	412.50	294.27	64375.	800.00	25.00	3862.51	* 0. 0.00*
	415.00	290.78					*
11	422.75	280.97	221313.	800.00	25.00	4285.06	* 0. 0.00*
	430.49	271.16					*
12	431.44	270.06	29491.	800.00	25.00	4677.86	* 0. 0.00*
	432.39	268.96					*
13	433.69	267.46	41584.	800.00	25.00	4771.51	* 0. 0.00*
	435.00	265.96					*
14	437.50	263.19	83024.	800.00	25.00	4981.42	* 0. 0.00*
	440.00	260.42					*
15	442.50	257.76	88156.	800.00	25.00	5289.35	* 0. 0.00*
	445.00	255.10					*
16	447.50	252.55	92500.	800.00	25.00	5549.99	* 0. 0.00*
	450.00	250.00					*
17	450.00	250.00	27.	800.00	25.00	5658.72	* 0. 0.00*
	450.00	250.00					*
18	451.57	248.45	59596.	800.00	25.00	5696.17	* 0. 0.00*
	453.14	246.90					*
19	454.07	246.00	35679.	2761.50	0.00	0.00	* 0. 0.00*
	455.00	245.10					*
20	460.00	240.48	192494.	2735.23	0.00	0.00	* 0. 0.00*
	465.00	235.85					*
21	471.40	230.43	249317.	2685.97	0.00	0.00	* 0. 0.00*
	477.80	225.00					*
22	487.79	217.49	399475.	350.00	28.00	6659.31	* 0. 0.00*
	497.78	209.99					*
23	508.28	203.21	427716.	350.00	28.00	7532.14	* 0. 0.00*
	518.78	196.43					*

## S L I C E I N F O R M A T I O N

NO.	X		Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES*	
	LEFT CENTER RIGHT	LEFT CENTER RIGHT						AT SURFACE	
								*****	
								FORCE-LOCATION*	
								(LBS)	X
	518.78	196.43						*	*
24	529.73	190.40	449527.	350.00	28.00	8170.27	*	0.	0.00*
	540.68	184.38					*		*
25	552.03	179.15	464126.	350.00	28.00	8693.37	*	0.	0.00*
	563.37	173.91					*		*
26	575.06	169.49	470916.	350.00	28.00	9058.35	*	0.	0.00*
	586.75	165.07					*		*
27	593.38	162.98	261783.	350.00	28.00	9375.73	*	0.	0.00*
	600.09	160.88					*		*
28	601.13	160.56	44287.	350.00	28.00	9451.55	*	0.	0.00*
	602.26	160.23					*		*
29	614.39	157.20	472264.	2428.02	0.00	0.00	*	0.	0.00*
	626.51	154.17					*		*
30	629.00	153.66	96258.	2463.41	0.00	0.00	*	0.	0.00*
	631.49	153.15					*		*
31	643.83	151.16	470214.	8089.23	0.00	0.00	*	0.	0.00*
	656.17	149.18					*		*
32	668.61	148.07	459482.	8239.58	0.00	0.00	*	0.	0.00*
	681.06	146.96					*		*
33	690.53	146.70	336203.	8331.47	0.00	0.00	*	0.	0.00*
	700.00	146.45					*		*
34	712.49	146.89	420989.	8379.76	0.00	0.00	*	0.	0.00*
	724.98	147.33					*		*
35	737.41	148.65	388649.	8392.52	0.00	0.00	*	0.	0.00*
	749.83	149.98					*		*
36	749.92	149.99	2492.	8387.18	0.00	0.00	*	0.	0.00*
	750.00	150.00					*		*
37	762.30	152.20	349276.	8359.10	0.00	0.00	*	6636.	766.40*
	774.60	154.41					*		*
38	786.72	157.48	304285.	8282.25	0.00	0.00	*	19507.	788.05*
	798.83	160.54					*		*
39	810.70	164.46	254484.	8164.20	0.00	0.00	*	31590.	811.48*
	822.57	168.37					*		*
40	823.78	168.83	23448.	8087.46	0.00	0.00	*	3931.	823.79*
	825.00	169.28					*		*
41	830.42	171.43	100545.	8039.47	0.00	0.00	*	16906.	830.42*
	835.84	173.58					*		*
42	847.20	178.79	190265.	2212.10	0.00	0.00	*	35447.	847.20*
	858.56	184.00					*		*
43	860.82	185.15	34363.	2148.47	0.00	0.00	*	7061.	860.82*
	863.09	186.31					*		*
44	873.96	192.46	146673.	350.00	28.00	5095.30	*	33938.	873.96*
	884.84	198.61					*		*
45	895.26	205.52	109159.	350.00	28.00	3253.58	*	32497.	895.26*
	905.67	212.43					*		*
46	913.94	218.71	61542.	350.00	28.00	1850.16	*	25788.	913.94*
	922.20	225.00					*		*
47	931.64	233.19	38066.	2110.86	0.00	0.00	*	23443.	931.64*
	941.08	241.39					*		*
48	945.54	245.69	4611.	2207.84	0.00	0.00	*	13917.	945.54*
	950.00	250.00					*		*

## ITERATION INFORMATION

ITER	F	THETA (RADIAN DEGREES)	DELTA (RADIAN)	DELTA (RADIAN)	FORCE IMBAL (LBS.)	MOMENT IMBAL (FT.LBS.)
1	2.5000	.34907	20.000			
				-.8313 -.6886 -.6161 -.6161	-.16405 -.19506 -.17453 -.17453	-65293. 108526661. SECOND ORDER CORRECTION FACTORED VALUES ADJUSTED VALUES
2	1.8839	.17453	10.000			
				.0257 .0261 .0261	.01235 .01232 .01232	-947. -10257710. SECOND ORDER CORRECTION SECOND ORDER CORRECTION
3	1.9100	.18685	10.706			
				-.0000 -.0000	-.00061 -.00001	-2. 4558. SECOND ORDER CORRECTION
4	1.9100	.18684	10.705			
				.0000	-.00000	0. 0.

.083 SECONDS REQUIRED IN CALCFS

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = 1.910 ( 4 ITERATIONS)

SIDE FORCE INCLINATION = 10.71 DEGREES

SLICE NO.	XAVG	NORMAL STRESS (PSF)	SHEAR STRESS (PSF)	* L I N E O F T H R U S T *	* E-FORCE (LBS)
				*****	
				X YI(TOT) FRACTION	
0				366.3 383.2 0.0000	0.
1	370.9	1562.	42.	375.4 371.6 .4203	38699.
2	380.2	3614.	345.	385.0 356.6 .3234	110640.
3	387.5	5154.	612.	390.0 349.5 .2994	156504.
4	392.3	6147.	808.	394.6 343.3 .2844	202638.
5	394.8	6798.	812.	395.0 342.8 .2831	207116.
6	397.5	7303.	894.	400.0 336.5 .2705	263023.
7	401.4	7979.	997.	402.8 333.1 .2693	295477.
8	403.9	7837.	1449.	405.0 330.8 .2709	318714.
9	407.5	8176.	1508.	410.0 325.8 .2740	371399.
10	412.5	8664.	1591.	415.0 321.0 .2766	423979.
11	422.7	9958.	1804.	430.5 307.1 .2793	591338.
12	431.4	11167.	2003.	432.4 305.5 .2791	612216.
13	433.7	11461.	2052.	435.0 303.3 .2788	641167.
14	437.5	12090.	2154.	440.0 299.2 .2777	697404.
15	442.5	13005.	2303.	445.0 295.1 .2761	755014.
16	447.5	13811.	2436.	450.0 291.2 .2743	813299.
17	450.0	14162.	2495.	450.0 291.2 .2743	813316.
18	451.6	14304.	2520.	453.1 288.7 .2761	849744.
19	454.1	15263.	1446.	455.0 287.2 .2761	874541.
20	460.0	15480.	1432.	465.0 279.4 .2781	1003378.
21	471.4	15992.	1406.	477.8 270.6 .2829	1158926.
22	487.8	16117.	2816.	497.8 259.7 .2995	1344598.
23	508.3	17006.	2821.	518.8 249.6 .3143	1516023.
24	529.7	17668.	2827.	540.7 240.3 .3283	1666916.
25	552.0	18107.	2804.	563.4 231.9 .3420	1792814.
26	575.1	18312.	2759.	586.8 224.3 .3558	1890141.
27	593.4	18328.	2675.	600.0 220.5 .3635	1931504.
28	601.1	18311.	2650.	602.3 219.9 .3640	1937572.
29	614.4	18523.	1271.	626.5 212.9 .3626	2018927.
30	629.0	18591.	1290.	631.5 211.6 .3623	2031482.
31	643.8	18607.	4235.	656.2 207.8 .3733	2000906.
32	668.6	18574.	4314.	681.1 205.1 .3849	1934743.
33	690.5	18368.	4362.	700.0 203.7 .3945	1861459.
34	712.5	17958.	4387.	725.0 202.9 .4089	1735999.
35	737.4	17283.	4394.	749.8 203.3 .4266	1581054.
36	749.9	16861.	4391.	750.0 203.3 .4268	1579922.
37	762.3	16643.	4377.	774.6 204.9 .4496	1396795.
38	786.7	16056.	4336.	798.8 207.8 .4815	1187060.
39	810.7	15232.	4275.	822.6 212.3 .5332	956328.
40	823.8	14702.	4234.	825.0 212.9 .5406	931440.
41	830.4	14384.	4209.	835.8 216.1 .5570	823952.
42	847.2	11696.	1158.	858.6 219.6 .5389	675842.
43	860.8	11001.	1125.	863.1 220.3 .5340	645315.
44	874.0	10791.	1769.	884.8 225.5 .5238	474040.
45	895.3	9702.	1978.	905.7 232.2 .5255	298816.
46	913.9	8394.	2005.	922.2 239.3 .5739	160144.
47	931.6	5677.	1105.	941.1 246.5 .5979	46259.
48	945.5	4173.	1156.	950.0 250.0 0.0000	-0.

0.000 SECONDS REQUIRED IN FINAL

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

## \*\*\* INITIAL SEARCH INFORMATION \*\*\*

X COORDINATE FOR CENTER OF FIRST GRID - - - - -	650.00 FT
Y COORDINATE FOR CENTER OF FIRST GRID - - - - -	450.00 FT
ALL CIRCLES TANGENT TO A ROCKLINE AT ELEVATION, Y - - - -	200.00 FT
OVERALL CRITICAL CIRCLE LOCATED	
NO CIRCLE ALLOWED TO PASS BELOW ELEVATION, Y - - - - -	50.00 FT
REQUIRED ACCURACY IN CRITICAL CENTER LOCATION - - - - -	10.00 FT
TIME LIMIT - - - - -	90.00 SECS.
CONSTANT SUBTENDED ANGLE SPECIFIED AS - - - - -	4.00 DEGREES
ASSUMED DEPTH OF TENSION CRACK - - - - -	0.00 FT
ASSUMED DEPTH OF WATER IN TENSION CRACK - - - - -	0.00 FT
UNIT WEIGHT OF WATER - - - - -	62.40 PCF
INITIAL ASSUMED VALUE FOR FACTOR OF SAFETY - - - - -	2.50
INITIAL ASSUMED VALUE FOR SIDE FORCE INCLINATION - - - -	20.00 DEGREES
ITERATION LIMIT - - - - -	30
ALLOWED FORCE IMBALANCE SPECIFIED - - - - -	100.00 LBS.
ALLOWED MOMENT IMBALANCE SPECIFIED - - - - -	200.00 FT-LBS.

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

FOR ROCKLINE ELEVATION = 200. FEET

\*\*\*\*\*

\*\*\* C I R C L E   D A T A   \*\*\* SOLN. DATA   \*\*\* M E S S A G E S

XC	YC	RADIUS	F	THETA	I
*****					
450.00	250.00	50.00			
650.00	250.00	50.00			
850.00	250.00	50.00			
450.00	450.00	250.00	3.791	6.58	5
650.00	450.00	250.00	1.413	13.30	6
850.00	450.00	250.00	4.329	5.14	6
450.00	650.00	450.00	3.480	7.52	4
650.00	650.00	450.00	1.318	11.66	6
850.00	650.00	450.00			
CIRCLE DOES NOT INTERSECT SLOPE					
***** SPECIFIED STARTING POINT					
FOR GRID IS NOT OPTIMUM					
- RESET BY PROGRAM					
*****					
450.00	850.00	650.00			
650.00	850.00	650.00	1.597	10.10	4
850.00	850.00	650.00			
CIRCLE DOES NOT INTERSECT SLOPE					
*****					
600.00	600.00	400.00	1.557	11.51	4
650.00	600.00	400.00	1.270	12.27	3
700.00	600.00	400.00	1.298	12.41	3
600.00	650.00	450.00	1.628	11.22	4
700.00	650.00	450.00	1.305	11.83	3
600.00	700.00	500.00	1.667	10.96	4
650.00	700.00	500.00	1.381	11.15	3
700.00	700.00	500.00	1.320	11.25	3
*****					
600.00	550.00	350.00	1.488	11.85	4
650.00	550.00	350.00	1.289	13.04	3
700.00	550.00	350.00	1.303	12.85	3
*****					
620.00	570.00	370.00	1.377	12.14	3
650.00	570.00	370.00	1.285	12.74	3
680.00	570.00	370.00	1.292	12.87	3
620.00	600.00	400.00	1.411	11.89	3
680.00	600.00	400.00	1.291	12.48	3
620.00	630.00	430.00	1.450	11.67	3
650.00	630.00	430.00	1.294	11.89	3
680.00	630.00	430.00	1.293	12.07	3
*****					
640.00	590.00	390.00	1.293	12.32	3
650.00	590.00	390.00	1.275	12.43	2
660.00	590.00	390.00	1.287	12.54	3
640.00	600.00	400.00	1.302	12.19	3
660.00	600.00	400.00	1.288	12.40	3
640.00	610.00	410.00	1.313	12.07	3
650.00	610.00	410.00	1.273	12.13	2
660.00	610.00	410.00	1.286	12.25	3
*****					

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

FOR FIXED RADIUS = 400.00 FEET

\*\*\*\*\*

\*\*\* C I R C L E O A T A \*\*\* SOLN. DATA \*\*\* M E S S A G E S

XC YC RADIUS F THETA I

\*\*\*\*\*

ITERATION 1 SLICES WITH LOW DENOMINATOR - 4,

450.00	400.00	400.00				SOLUTION DID NOT CONVERGE
650.00	400.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE
850.00	400.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE
450.00	600.00	400.00	3.503	7.38	5	
850.00	600.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE
450.00	800.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE
650.00	800.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE
850.00	800.00	400.00				CIRCLE DOES NOT INTERSECT SLOPE

\*\*\*\*\*

600.00	550.00	400.00	1.590	9.39	4
650.00	550.00	400.00	1.698	9.94	4
700.00	550.00	400.00	1.864	10.27	5
600.00	600.00	400.00	1.557	11.51	4
700.00	600.00	400.00	1.298	12.41	3
600.00	650.00	400.00	1.776	13.41	5
650.00	650.00	400.00	1.521	15.23	4
700.00	650.00	400.00	1.386	16.32	3

\*\*\*\*\*

620.00	570.00	400.00	1.529	10.61	4
650.00	570.00	400.00	1.460	10.72	4
680.00	570.00	400.00	1.353	10.66	3
620.00	600.00	400.00	1.411	11.89	3
680.00	600.00	400.00	1.291	12.48	3
620.00	630.00	400.00	1.083	12.15	3
650.00	630.00	400.00	1.087	13.25	3
680.00	630.00	400.00	1.085	14.10	3

\*\*\*\*\*

590.00	600.00	400.00	1.642	11.33	4
590.00	630.00	400.00	1.068	10.72	3
590.00	660.00	400.00	1.761	13.26	4
620.00	660.00	400.00	1.576	14.38	5
650.00	660.00	400.00	1.459	15.61	5

\*\*\*\*\*

560.00	600.00	400.00	1.757	10.56	4
560.00	630.00	400.00	1.147	9.52	3
560.00	660.00	400.00	1.982	12.10	4

\*\*\*\*\*

580.00	620.00	400.00	1.370	11.20	4
590.00	620.00	400.00	1.302	11.37	4
600.00	620.00	400.00	1.246	11.55	3
580.00	630.00	400.00	1.034	9.99	3
600.00	630.00	400.00	1.074	11.23	3
580.00	640.00	400.00	1.328	11.37	4
590.00	640.00	400.00	1.309	11.91	4
600.00	640.00	400.00	1.289	12.42	4

\*\*\*\*\*

ITERATION 3 SLICES WITH LOW DENOMINATOR - 34,

ITERATION 6 SLICES WITH LOW DENOMINATOR - 29,

ITERATION 9 SLICES WITH LOW DENOMINATOR - 29,

ITERATION 10 SLICES WITH LOW DENOMINATOR - 34,35,36,

ITERATION 11 SLICES WITH LOW DENOMINATOR - 34,35,36,

570.00	620.00	400.00				SOLUTION DID NOT CONVERGE
570.00	630.00	400.00	1.085	9.74	3	
570.00	640.00	400.00	1.349	10.85	4	

\*\*\*\*\*

\*\*\*\*\* CAUTION - F COULD NOT BE COMPUTED FOR SOME OF GRID POINTS AROUND MINIMUM

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

FOR ROCKLINE ELEVATION = 230. FEET

\*\*\*\*\*

\*\*\* C I R C L E   D A T A \*\*\* SOLN. DATA   \*\*\* M E S S A G E S

XC	YC	RADIUS	F	THETA	I
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\*\*\*\*\*

ITERATION 3 SLICES WITH LOW DENOMINATOR - 3, 4,  
 380.00 430.00 200.00 SOLUTION DID NOT CONVERGE  
 580.00 430.00 200.00 1.203 11.09 4  
 780.00 430.00 200.00 SOLUTION DID NOT CONVERGE  
 380.00 630.00 400.00 SOLUTION DID NOT CONVERGE  
 780.00 630.00 400.00 1.534 13.40 5  
 380.00 830.00 600.00 SOLUTION DID NOT CONVERGE  
 580.00 830.00 600.00 1.229 10.05 3  
 780.00 830.00 600.00 1.375 12.59 4  
 \*\*\*\*\*

530.00	580.00	350.00	1.341	8.74	4
580.00	580.00	350.00	1.059	10.42	3
630.00	580.00	350.00	1.067	12.98	3
530.00	630.00	400.00	1.390	8.91	5
630.00	630.00	400.00	1.088	12.56	3

ITERATION 3 SLICES WITH LOW DENOMINATOR - 30,31,32,

ITERATION 4 SLICES WITH LOW DENOMINATOR - 31,32,

ITERATION 5 SLICES WITH LOW DENOMINATOR - 30,31,32,

ITERATION 6 SLICES WITH LOW DENOMINATOR - 30,31,32,

ITERATION 7 SLICES WITH LOW DENOMINATOR - 30,31,32,  
 530.00 680.00 450.00 SOLUTION DID NOT CONVERGE  
 580.00 680.00 450.00 1.079 9.99 3  
 630.00 680.00 450.00 1.109 12.13 3  
 \*\*\*\*\*

550.00	600.00	370.00	1.189	9.22	3
580.00	600.00	370.00	1.048	10.24	3
610.00	600.00	370.00	1.070	11.95	3
550.00	630.00	400.00	1.217	9.31	4
610.00	630.00	400.00	1.079	11.71	3
550.00	660.00	430.00	1.246	9.38	4
580.00	660.00	430.00	1.060	9.99	3
610.00	660.00	430.00	1.089	11.49	3

\*\*\*\*\*

570.00	620.00	390.00	1.076	9.73	3
580.00	620.00	390.00	1.038	10.07	2
590.00	620.00	390.00	1.067	10.79	3
570.00	630.00	400.00	1.085	9.74	3
590.00	630.00	400.00	1.068	10.72	3
570.00	640.00	410.00	1.094	9.75	3
580.00	640.00	410.00	1.042	9.98	3
590.00	640.00	410.00	1.065	10.63	3

\*\*\*\*\*

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

\*\*\*\*\* CRITICAL CIRCLE INFORMATION \*\*\*\*\*

X COORDINATE OF CENTER - - - - -	580.00
Y COORDINATE OF CENTER - - - - -	630.00
RADIUS - - - - -	400.00
FACTOR OF SAFETY - - - - -	1.034
SIDE FORCE INCLINATION (DEGREES) - -	9.99
SECONDS REQUIRED TO LOCATE CIRCLE -	14.890

## S L I C E I N F O R M A T I O N

NO.	X	Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES* * AT SURFACE *
	LEFT CENTER RIGHT	LEFT CENTER RIGHT					* FORCE-LOCATION* * (LBS) X *
	296.21	348.11					*
1	306.39	338.55	40240.	0.00	40.00	3522.40	* 59367. 305.98*
	316.57	329.00					*
2	327.39	320.18	127126.	0.00	40.00	4669.08	* 47262. 326.76*
	338.21	311.35					*
3	349.61	303.31	220234.	0.00	40.00	5721.56	* 32143. 348.54*
	361.02	295.26					*
4	372.96	288.03	317426.	0.00	40.00	6674.73	* 14193. 370.17*
	384.91	280.80					*
5	384.95	280.78	1420.	0.00	40.00	7127.51	* 17. 384.95*
	385.00	280.75					*
6	386.91	279.70	58655.	0.00	40.00	7194.84	* 412. 386.52*
	388.82	278.65					*
7	389.41	278.33	18521.	0.00	35.00	7280.48	* 24. 389.21*
	390.00	278.01					*
8	392.50	276.68	79971.	0.00	35.00	7383.23	* 0. 0.00*
	395.00	275.35					*
9	396.58	274.54	51853.	0.00	35.00	7516.93	* 0. 0.00*
	398.16	273.72					*
10	399.08	273.25	30432.	800.00	25.00	4968.99	* 0. 0.00*
	400.00	272.79					*
11	402.50	271.55	82226.	800.00	25.00	4933.55	* 0. 0.00*
	405.00	270.31					*
12	407.50	269.12	81342.	800.00	25.00	4880.51	* 0. 0.00*
	410.00	267.92					*
13	412.50	266.77	80876.	800.00	25.00	4852.54	* 0. 0.00*
	415.00	265.62					*
14	424.47	261.62	314673.	800.00	25.00	4981.79	* 0. 0.00*
	433.95	257.62					*
15	434.47	257.41	17976.	800.00	25.00	5133.18	* 0. 0.00*
	435.00	257.21					*
16	437.50	256.25	87186.	800.00	25.00	5231.13	* 0. 0.00*
	440.00	255.30					*
17	442.50	254.38	90182.	800.00	25.00	5410.89	* 0. 0.00*
	445.00	253.47					*
18	447.50	252.59	92476.	800.00	25.00	5548.56	* 0. 0.00*
	450.00	251.71					*
19	452.50	250.87	93215.	800.00	25.00	5598.05	* 0. 0.00*
	455.00	250.03					*
20	455.00	250.03	86.	0.00	35.00	0.00	* 0. 0.00*
	455.00	250.03					*
21	455.05	250.02	1867.	0.00	35.00	0.00	* 0. 0.00*
	455.10	250.00					*
22	460.05	248.44	180957.	2038.45	0.00	0.00	* 0. 0.00*
	465.00	246.89					*
23	478.50	243.34	472471.	1950.67	0.00	0.00	* 0. 0.00*
	492.00	239.80					*
24	505.72	237.21	454256.	1822.67	0.00	0.00	* 0. 0.00*
	519.44	234.61					*
25	533.30	232.98	426165.	1734.17	0.00	0.00	* 0. 0.00*
	547.17	231.35					*
26	561.11	230.69	388593.	1654.17	0.00	0.00	* 0. 0.00*
	575.05	230.03					*
27	577.53	230.02	64311.	1607.08	0.00	0.00	* 0. 0.00*
	580.00	230.00					*
28	590.00	230.25	244200.	1600.00	0.00	0.00	* 0. 0.00*
	600.00	230.50					*
29	613.91	231.68	301907.	1600.00	0.00	0.00	* 0. 0.00*
	627.82	232.87					*
30	641.61	235.02	257805.	1600.00	0.00	0.00	* 0. 0.00*
	655.40	237.17					*
31	669.01	240.28	205822.	1622.93	0.00	0.00	* 0. 0.00*
	682.62	243.39					*
32	693.76	246.69	128701.	1652.24	0.00	0.00	* 0. 0.00*
	704.90	250.00					*
33	718.00	254.82	99420.	500.00	26.00	721.64	* 0. 0.00*
	731.10	259.64					*
34	740.55	263.78	33398.	500.00	26.00	280.98	* 0. 0.00*
	750.00	267.92					*
35	754.33	270.02	3768.	500.00	26.00	63.90	* 821. 755.77*
	758.66	272.11					*



## ITERATION INFORMATION

ITER	F	THETA (RADIANS DEGREES)	DELF	DELT (RADIAN)	FORCE IMBAL (LBS.)	MOMENT IMBAL (FT.LBS.)
1	1.0335	.17427	9.985	-.0000	-.00000	0.

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = 1.034 ( 1 ITERATIONS)

SIDE FORCE INCLINATION = 9.99 DEGREES

SLICE NO.	XAVG	NORMAL STRESS (PSF)	SHEAR STRESS (PSF)	* L I N E O F T H R U S T *			* E-FORCE (LBS)
				X	YT(TDT)	FRACTION	
0				296.2	348.1	0.0000	0.
1	306.4	3663.	114.	316.6	340.6	.3960	94225.
2	327.4	6063.	1132.	338.2	331.6	.3501	197041.
3	349.6	8534.	2283.	361.5	322.1	.3147	297435.
4	373.0	11065.	3565.	384.9	312.6	.2845	378648.
5	385.0	12376.	4261.	385.0	312.5	.2844	378905.
6	386.9	12583.	4374.	388.8	311.1	.2801	388872.
7	389.4	13034.	3898.	390.0	310.6	.2783	392626.
8	392.5	13323.	4024.	395.3	308.4	.2708	407851.
9	396.6	13720.	4203.	398.2	307.1	.2666	416950.
10	399.1	13764.	4742.	408.0	306.5	.2649	421062.
11	402.5	13734.	4745.	405.0	304.8	.2658	431343.
12	407.5	13684.	4746.	400.0	303.2	.2673	440318.
13	412.5	13703.	4767.	415.0	301.7	.2684	448077.
14	424.5	14315.	4985.	433.9	296.7	.2745	468136.
15	434.5	14964.	5210.	435.0	296.5	.2749	468803.
16	437.5	15316.	5324.	443.0	295.4	.2769	471386.
17	442.5	15957.	5532.	445.0	294.4	.2790	472926.
18	447.5	16478.	5705.	450.0	293.4	.2814	473325.
19	452.5	16739.	5801.	455.0	292.6	.2889	472470.
20	455.0	16068.	10886.	455.0	292.6	.2889	472444.
21	455.1	16067.	10885.	455.1	292.7	.2894	471663.
22	460.1	17061.	1972.	465.0	288.0	.2826	505457.
23	478.5	16567.	1887.	492.0	278.4	.2771	571929.
24	505.7	16003.	1764.	519.4	271.3	.2810	606567.
25	533.3	15153.	1678.	547.2	266.3	.2909	609463.
26	561.1	14023.	1601.	575.1	262.8	.3055	583328.
27	577.5	13255.	1555.	580.0	262.4	.3085	576044.
28	590.0	12577.	1548.	600.0	261.0	.3224	538790.
29	613.9	11428.	1548.	627.8	260.1	.3285	468658.
30	641.6	10108.	1548.	655.4	260.3	.3339	382456.
31	669.0	8540.	1570.	682.6	261.4	.3339	286621.
32	693.8	6894.	1599.	704.9	262.6	.3141	205433.
33	718.0	5706.	2836.	731.1	267.2	.3497	76121.
34	740.6	3134.	1830.	750.0	270.8	.4003	15578.
35	754.3	1376.	1103.	758.7	272.1	0.0000	0.

SEARCH COMPLETED

F1 = 1.033530

THETA1 = 9.965209

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

## SPECIFIED SHEAR SURFACE COORDINATES

I	X	Y
1	375.00	387.50
2	475.00	200.00
3	500.00	175.00
4	525.00	165.00
5	550.00	160.00
6	575.00	155.00
7	600.00	155.00
8	800.00	175.00
9	950.00	250.00

ASSUMED DEPTH OF WATER IN TENSION CRACK - - - - - 0.00 FT  
 UNIT WEIGHT OF WATER - - - - - 62.40 PCF  
 INITIAL ASSUMED VALUE FOR FACTOR OF SAFETY - - - - - 2.50  
 INITIAL ASSUMED VALUE FOR SIDE FORCE INCLINATION - - - - 20.00 DEGREES  
 ITERATION LIMIT - - - - - 30  
 ALLOWED FORCE IMBALANCE SPECIFIED - - - - - 100.00 LBS.  
 ALLOWED MOMENT IMBALANCE SPECIFIED - - - - - 200.00 FT-LBS.

## SHEAR SURFACE COORDINATES

I	X	Y
1	375.00	387.50
2	385.00	368.75
3	390.00	359.38
4	395.00	350.00
5	397.67	345.00
6	400.00	340.63
7	405.00	331.25
8	405.67	330.00
9	410.00	321.88
10	415.00	312.50
11	430.35	283.72
12	435.00	275.00
13	440.00	265.63
14	445.00	256.25
15	448.33	250.00
16	450.00	246.88
17	451.47	244.12
18	455.00	237.50
19	461.67	225.00
20	465.00	218.75
21	475.00	200.00
22	500.00	175.00
23	525.00	165.00
24	550.00	160.00
25	566.67	156.67
26	575.00	155.00
27	600.00	155.00
28	750.00	170.00
29	800.00	175.00
30	812.50	181.25
31	825.00	187.50
32	900.00	225.00
33	950.00	250.00

.067 SECONDS REQUIRED IN GENER2

.046 SECONDS REQUIRED IN SSOATA

## S L I C E I N F O R M A T I O N

NO.	X	Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES*	
	LEFT CENTER RIGHT	LEFT CENTER RIGHT					AT SURFACE	
							*****	
							FORCE-LOCATION	
							(LBS)	X
	375.00	387.50						
1	380.00	378.13	16031.	0.00	40.00	1053.00	* 3488.	379.17*
	385.00	368.75						
2	387.50	364.06	20039.	0.00	40.00	1930.50	* 436.	386.67*
	390.00	359.38						
3	392.50	354.69	28055.	0.00	40.00	2515.50	* 0.	0.00*
	395.00	350.00						
4	396.33	347.50	18240.	0.00	40.00	2964.00	* 0.	0.00*
	397.67	345.00						
5	398.83	342.81	17703.	0.00	35.00	3256.50	* 0.	0.00*
	400.00	340.63						
6	402.50	335.94	42109.	0.00	35.00	3685.50	* 0.	0.00*
	405.00	331.25						
7	405.33	330.63	6012.	0.00	35.00	4017.00	* 0.	0.00*
	405.67	330.00						
8	407.83	325.94	40842.	800.00	25.00	2827.50	* 0.	0.00*
	410.00	321.88						
9	412.50	317.19	50625.	800.00	25.00	3037.50	* 0.	0.00*
	415.00	312.50						
10	422.67	298.11	187666.	800.00	25.00	3668.02	* 0.	0.00*
	430.35	283.72						
11	432.67	279.36	67334.	800.00	25.00	4343.02	* 0.	0.00*
	435.00	275.00						
12	437.50	270.31	78750.	800.00	25.00	4725.00	* 0.	0.00*
	440.00	265.63						
13	442.50	260.94	86250.	800.00	25.00	5175.00	* 0.	0.00*
	445.00	256.25						
14	446.67	253.13	61375.	800.00	25.00	5523.75	* 0.	0.00*
	448.33	250.00						
15	449.17	248.44	31719.	800.00	25.00	5709.37	* 0.	0.00*
	450.00	246.88						
16	450.74	245.50	28492.	800.00	25.00	5812.28	* 0.	0.00*
	451.47	244.12						
17	453.24	240.81	70021.	3055.42	0.00	0.00	* 0.	0.00*
	455.00	237.50						
18	458.33	231.25	136917.	3055.42	0.00	0.00	* 0.	0.00*
	461.67	225.00						
19	463.33	221.88	70256.	350.00	28.00	6587.69	* 0.	0.00*
	465.00	218.75						
20	470.00	209.38	220169.	350.00	28.00	7406.70	* 0.	0.00*
	475.00	200.00						
21	487.50	187.50	586406.	350.00	28.00	8779.12	* 0.	0.00*
	500.00	175.00						
22	512.50	170.00	598281.	350.00	28.00	9814.57	* 0.	0.00*
	525.00	165.00						
23	537.50	162.50	581436.	350.00	28.00	9994.72	* 0.	0.00*
	550.00	160.00						
24	558.33	158.33	374236.	350.00	28.00	10003.86	* 0.	0.00*
	566.67	156.67						
25	570.83	155.83	183212.	2441.67	0.00	0.00	* 0.	0.00*
	575.00	155.00						
26	587.50	155.00	527031.	2450.00	0.00	0.00	* 0.	0.00*
	600.00	155.00						
27	675.00	162.50	2458125.	2375.00	0.00	0.00	* 0.	0.00*
	750.00	170.00						
28	775.00	172.50	556875.	2275.00	0.00	0.00	* 27406.	783.33*
	800.00	175.00						
29	806.25	178.13	114805.	2218.75	0.00	0.00	* 15416.	806.48*
	812.50	181.25						
30	818.75	184.38	99102.	350.00	28.00	6359.19	* 18842.	818.94*
	825.00	187.50						
31	862.50	206.25	386719.	350.00	28.00	3562.50	* 117000.	862.50*
	900.00	225.00						
32	925.00	237.50	75000.	1785.04	0.00	0.00	* 78000.	925.00*
	950.00	250.00						

## ITERATION INFORMATION

ITER	F	THETA (RADIAN DEGREES)	DELF	DELT (RADIAN)	FORCE IMBAL (LBS.)	MOMENT IMBAL (FT.LBS.)
1	2.5000	.34907	20.000			
			-3.5435	-.37167	-457084.	-83245772.
			-1.0000	-.10472	FACTURED VALUES	
			-1.0000	-.10472	ADJUSTED VALUES	
2	1.5000	.24435	14.000			
			-.2348	-.07863	-62322.	25624698.
			-.2031	-.07680	SECOND ORDER CORRECTION	
			-.2025	-.07679	SECOND ORDER CORRECTION	
3	1.2975	.16755	9.600			
			.0069	.00254	3788.	-465960.
			.0070	.00255	SECOND ORDER CORRECTION	
4	1.3045	.17011	9.746			
			-.0000	-.00000	-0.	11.

.083 SECONDS REQUIRED IN CALCFS

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = 1.304 ( 4 ITERATIONS)

SIDE FORCE INCLINATION = 9.75 DEGREES

SLICE NO.	XAVG	NCRMAL STRESS (PSF)	SHEAR STRESS (PSF)	* LINE OF THRUST *	* E-FORCE (LBS) *
				X YT(TOT) FRACTION	
0				375.0 387.5 0.0000	0.
1	380.0	1258.	132.	385.0 377.9 .3858	23832.
2	387.5	2562.	406.	390.0 370.7 .3178	46015.
3	392.5	3461.	608.	395.0 363.8 .2898	75419.
4	396.3	4172.	777.	397.7 360.1 .2806	94206.
5	398.8	4724.	788.	400.0 356.9 .2734	113037.
6	402.5	5273.	852.	405.0 350.1 .2749	158209.
7	405.3	5675.	890.	405.7 349.3 .2752	164709.
8	407.8	5232.	1473.	410.0 344.4 .2882	200835.
9	412.5	5660.	1551.	415.0 338.6 .2983	246148.
10	422.7	6948.	1786.	430.3 319.8 .3105	418689.
11	432.7	8326.	2037.	435.0 313.8 .3102	481824.
12	437.5	9106.	2179.	440.0 307.2 .3091	556293.
13	442.5	10024.	2347.	445.0 300.4 .3071	638536.
14	446.7	10736.	2477.	448.3 295.9 .3057	697385.
15	449.2	11115.	2546.	450.0 293.6 .3051	727878.
16	450.7	11325.	2584.	451.5 291.6 .3060	755306.
17	453.2	11989.	2342.	455.0 286.7 .3072	826377.
18	458.3	12517.	2342.	461.7 277.5 .3105	967222.
19	463.3	12495.	2676.	465.0 273.3 .3137	1036395.
20	470.0	13244.	2647.	475.0 260.4 .3223	1258247.
21	487.5	17357.	3765.	500.0 241.1 .3304	1598053.
22	512.5	21333.	4963.	525.0 233.1 .3450	1687302.
23	537.5	22339.	5300.	550.0 229.7 .3663	1666499.
24	558.3	21572.	4984.	566.7 227.3 .3819	1655346.
25	570.8	21204.	1872.	575.0 225.0 .3838	1675088.
26	587.5	21404.	1878.	600.0 222.7 .3983	1628135.
27	675.0	17177.	1821.	750.0 219.8 .4746	1097377.
28	775.0	12374.	1744.	800.0 217.9 .5143	939642.
29	806.3	12650.	1701.	812.5 220.1 .5332	834441.
30	818.8	12305.	2692.	825.0 223.1 .5689	717926.
31	862.5	9247.	2585.	900.0 241.8 .6717	177248.
32	925.0	4353.	1368.	950.0 -210.6 0.0000	0.

.091 SECONDS REQUIRED IN FINALD

```

*****
*
*   PROGRAM GENSAM
*
*   SPENCER'S METHOD OF SLOPE STABILITY ANALYSIS
*
*   FOR GENERALIZED FAILURE SURFACES
*
*   LATEST REVISION - 3/ 1/76
*
*   DATE RUN - 21/03/77      TIME RUN - 16.36.13.
*
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0999999999 GSS 031776 EXAMPLE PROB. A - SOIL PROFILE NO. 2

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PROFILE LINE NO.	MATERIAL TYPE	X	Y	COORDINATES X	COORDINATES Y	X	Y
1	1	100.00	250.00	400.00	400.00	405.00	400.00
2	2	385.00	250.00	405.00	400.00	415.00	400.00
3	3	395.00	250.00	415.00	400.00	435.00	400.00
4	2	435.00	400.00	445.00	400.00	465.00	250.00
5	4	445.00	400.00	450.00	400.00	600.00	325.00
6	5	0.00	250.00	395.00	250.00	410.00	225.00
7	5	440.00	225.00	455.00	250.00	1000.00	250.00
8	6	0.00	225.00	1000.00	225.00		
9	7	0.00	100.00	1000.00	200.00		
10	8	0.00	90.00	1000.00	190.00		
11	9	0.00	50.00	1000.00	100.00		
12	10	0.00	0.00	1000.00	0.00		
13	11	0.00	0.00	1000.00	0.00		

0999999999 GSS 031776 EXAMPLE PROB. A - SOIL PROFILE NO. 2

M A T E R I A L D A T A - T Y P E 1

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      0.00      0.00      0.00  
 PHI - - - - - 40.00 DEGREES  
 UNIT WEIGHT - - - - - 135.00 PCF  
 PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE  
 UNIT WEIGHT OF WATER - - - - 62.40 PCF

M A T E R I A L D A T A - T Y P E 2

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      0.00      0.00      0.00  
 PHI - - - - - 35.00 DEGREES  
 UNIT WEIGHT - - - - - 130.00 PCF  
 PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE  
 UNIT WEIGHT OF WATER - - - - 62.40 PCF

M A T E R I A L D A T A - T Y P E 3

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      800.00      0.00      0.00  
 PHI - - - - - 25.00 DEGREES  
 UNIT WEIGHT - - - - - 120.00 PCF  
 VALUE OF R-SUB-U - - - - - .30

M A T E R I A L D A T A - T Y P E 4

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      500.00      0.00      0.00  
 PHI - - - - - 26.00 DEGREES  
 UNIT WEIGHT - - - - - 123.00 PCF  
 VALUE OF R-SUB-U - - - - - .25

M A T E R I A L D A T A - T Y P E 5

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C          C/Z      REF. HT.  
       0.                      2500.00      0.00      0.00  
 PHI - - - - - 0.00 DEGREES  
 UNIT WEIGHT - - - - - 120.00 PCF  
 PORE PRESSURE - - - - - 0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   6

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    350.00     0.00        0.00  
 PHI - - - - -                    28.00 DEGREES  
 UNIT WEIGHT - - - - -            115.00 PCF  
 PORE PRESSURE DETERMINED FROM PIEZOMETRIC LINE  
 UNIT WEIGHT OF WATER - - - -     62.40 PCF

## M A T E R I A L   D A T A   -   T Y P E   7

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    2000.00    10.00        200.00  
 PHI - - - - -                    0.00 DEGREES  
 UNIT WEIGHT - - - - -            125.00 PCF  
 PORE PRESSURE - - - - -            0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   8

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    8000.00     0.00        0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI = 9  
 PHI - - - - -                    0.00 DEGREES  
 UNIT WEIGHT - - - - -            126.00 PCF  
 PORE PRESSURE - - - - -            0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   9

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    10000.00    0.00        0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI = 9  
 PHI - - - - -                    0.00 DEGREES  
 UNIT WEIGHT - - - - -            126.00 PCF  
 PORE PRESSURE - - - - -            0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   10

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    11000.00    0.00        0.00

UNDRAINED STRENGTH INTERPOLATED LINEARLY BETWEEN SOIL PROFILE LINES  
 INTERPOLATION MATERIALS USED HAVE KI = 9  
 PHI - - - - -                    0.00 DEGREES  
 UNIT WEIGHT - - - - -            126.00 PCF  
 PORE PRESSURE - - - - -            0.00 PSF

## M A T E R I A L   D A T A   -   T Y P E   11

COHESION (UNDRAINED STRENGTH) - ISOTROPIC  
                                   C            C/Z        REF. HT.  
           C.                    100000.00    0.00        0.00  
 PHI - - - - -                    0.00 DEGREES  
 UNIT WEIGHT - - - - -            150.00 PCF  
 PORE PRESSURE - - - - -            0.00 PSF

SURFACE PRESSURE DATA				
	X	Y	PRESSURE	MTYPE
	(MBPL1 OR MBPL2)			
1	0.00	250.00	9048.00	12
2	100.00	250.00	9048.00	12
3	390.00	395.00	0.00	12
4	750.00	275.00	0.00	13
5	825.00	250.00	1560.00	13
6	1000.00	250.00	1560.00	13

## PIEZOMETRIC ELEVATION DATA - NPIEZ = 14

	X	Y
1	0.00	395.00
2	414.33	395.00
3	750.00	275.00
4	1000.00	275.00

## 1 SLOPE(S) ANALYZED FOR SOIL PROFILE TITLED -

0999999999 GSS 031776 EXAMPLE PROB. A - SOIL PROFILE NO. 2

KEEP1 = 1 KEEP2 = 0 KEEP3 = 0

SLOPE DESIGNATION -  
EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT  
SLOPE POINTS

X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
0.00	250.00	100.00	250.00	400.00	400.00	450.00	400.00	600.00	325.00	825.00	250.00
1000.00	250.00										

1 SHEAR SURFACE(S) OR SEARCH(ES) CONSIDERED

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

## \*\*\* INITIAL SEARCH INFORMATION \*\*\*

X COORDINATE FOR CENTER OF FIRST GRID - - - - - 650.00 FT

Y COORDINATE FOR CENTER OF FIRST GRID - - - - - 475.00 FT

ALL CIRCLES PASS THROUGH THE FIXED POINT AT \*\* XFIX - - 825.00 FT  
YFIX - - 250.00 FT

SEARCH TERMINATED AFTER FIRST MODE SATISFIED

REQUIRED ACCURACY IN CRITICAL CENTER LOCATION - - - - - 10.00 FT

TIME LIMIT - - - - - 120.00 SECS.

CONSTANT SUBTENDED ANGLE SPECIFIED AS - - - - - 3.00 DEGREES

ASSUMED DEPTH OF TENSION CRACK - - - - - 0.00 FT

ASSUMED DEPTH OF WATER IN TENSION CRACK - - - - - 0.30 FT

UNIT WEIGHT OF WATER - - - - - 62.40 PCF

INITIAL ASSUMED VALUE FOR FACTOR OF SAFETY - - - - - 2.50

INITIAL ASSUMED VALUE FOR SIDE FORCE INCLINATION - - - - - 20.00 DEGREES

ITERATION LIMIT - - - - - 30

ALLOWED FORCE IMBALANCE SPECIFIED - - - - - 100.00 LBS.

ALLOWED MOMENT IMBALANCE SPECIFIED - - - - - 200.00 FT-LBS.



## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

FOR FIXED POINT OF INTERSECTION AT- X = 825.00 Y = 250.00

\*\*\*\*\*

\*\*\* C I R C L E O A T A \*\*\* SOLN. OATA \*\*\* M E S S A G E S

XC YC RADIUS F THETA I

\*\*\*\*\*

ITERATION 3 SLICES WITH LOW DENOMINATOR - 7, 8, 9,10,11,

ITERATION 4 SLICES WITH LOW DENOMINATOR - 2, 5, 6, 7, 8, 9,10,11,

ITERATION 5 SLICES WITH LOW DENOMINATOR - 5, 6, 7, 8, 9,10,11,

ITERATION 6 SLICES WITH LOW DENOMINATOR - 6, 7, 8, 9,10,11,12,

ITERATION 7 SLICES WITH LOW DENOMINATOR - 5, 6, 7, 8, 9,10,11,12,  
450.00 275.00 375.83 SOLUTION DID NOT CONVERGE

ITERATION 8 SLICES WITH LOW DENOMINATOR - 55,56,57,61,62,63,

ITERATION 9 SLICES WITH LOW DENOMINATOR - 54,55,56,57,61,62,

ITERATION 10 SLICES WITH LOW DENOMINATOR - 54,55,56,57,61,62,

ITERATION 11 SLICES WITH LOW DENOMINATOR - 54,55,56,57,61,62,					
650.00	275.00	176.78			SOLUTION DID NOT CONVERGE
850.00	275.00	35.35			SOLUTION DID NOT CONVERGE
450.00	475.00	437.32			SOLUTION DID NOT CONVERGE
650.00	475.00	285.04	1.264	12.63	6
850.00	475.00	226.38	14.459	7.75	15

ITERATION 12 SLICES WITH LOW DENOMINATOR - 4,

ITERATION 13 SLICES WITH LOW DENOMINATOR - 4,

ITERATION 14 SLICES WITH LOW DENOMINATOR - 4,

ITERATION 15 SLICES WITH LOW DENOMINATOR - 4,

ITERATION 16 SLICES WITH LOW DENOMINATOR - 1, 4, 5,					
450.00	675.00	566.79			SOLUTION DID NOT CONVERGE
650.00	675.00	459.62	1.225	11.54	5
850.00	675.00	425.73	3.344	13.98	5

\*\*\*\*\* SPECIFIED STARTING POINT  
FOR GRID IS NOT OPTIMUM  
- RESET BY PROGRAM

\*\*\*\*\*

450.00	875.00	728.67			SOLUTION DID NOT CONVERGE
650.00	875.00	649.04	1.315	10.48	5
850.00	875.00	625.50	1.766	18.29	5

\*\*\*\*\*

600.00	625.00	437.32	1.486	10.20	4
650.00	625.00	413.82	1.206	11.91	3
700.00	625.00	395.28	1.237	14.66	3
600.00	675.00	480.88	1.524	10.16	4
700.00	675.00	443.00	1.268	14.28	3
600.00	725.00	525.59	1.570	10.10	4
650.00	725.00	506.21	1.249	11.20	3
700.00	725.00	491.17	1.309	13.87	3

\*\*\*\*\*

600.00	575.00	395.28	1.460	10.23	4
650.00	575.00	369.12	1.199	12.28	3
700.00	575.00	348.21	1.223	14.81	3

\*\*\*\*\*

600.00	525.00	355.32	1.457	10.19	4
650.00	525.00	325.96	1.213	12.58	2
700.00	525.00	302.08	1.249	14.77	3

\*\*\*\*\*

620.00	545.00	359.23	1.387	11.12	4
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## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

\*\*\* C I R C L E     D A T A     \*\*\*\* SOLN. DATA     \*\*\*\* M E S S A G E S

XC	YC	RADIUS	F	THETA	I
650.00	545.00	343.00	1.204	12.47	2
680.00	545.00	328.71	1.186	13.99	3
620.00	575.00	384.25	1.383	11.06	4
680.00	575.00	355.88	1.179	13.83	2
620.00	605.00	409.94	1.387	10.97	4
650.00	605.00	395.79	1.202	12.06	3
680.00	605.00	383.47	1.182	13.60	2

\*\*\*\*\*

710.00	545.00	316.62	1.294	15.35	3
710.00	575.00	344.75	1.290	15.22	3
710.00	605.00	373.16	1.283	15.32	3

\*\*\*\*\*

670.00	565.00	351.07	1.175	13.36	3
680.00	565.00	346.77	1.180	13.89	3
690.00	565.00	342.71	1.195	14.39	3
670.00	575.00	360.07	1.175	13.29	2
690.00	575.00	351.92	1.192	14.35	3
670.00	585.00	369.12	1.175	13.21	2
680.00	585.00	365.03	1.179	13.76	2
690.00	585.00	361.18	1.190	14.29	3

\*\*\*\*\*

660.00	565.00	355.60	1.183	12.85	3
660.00	575.00	364.48	1.182	12.77	3
660.00	585.00	373.43	1.183	12.69	3

\*\*\*\*\*

## EXAMPLE PROBLEM A - EARTH DAM EMBANKMENT

\*\*\*\*\* CRITICAL CIRCLE INFORMATION \*\*\*\*\*

X COORDINATE OF CENTER - - - - -	670.00
Y COORDINATE OF CENTER - - - - -	575.00
RADIUS - - - - -	360.07
FACTOR OF SAFETY - - - - -	1.175
SIDE FORCE INCLINATION (DEGREES) - -	13.29
SECONDS REQUIRED TO LOCATE CIRCLE -	7.527

## S L I C E I N F O R M A T I O N

NO.	X		Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES*	
	LEFT CENTER RIGHT	LEFT CENTER RIGHT						AT SURFACE	
								*****	
								FORCE-LOCATION	
								(LBS) X	
	365.54	382.77						*	*
1	376.78	374.93	14788.	0.00	40.00	1252.12	*	7026.	370.30*
	376.02	367.10					*	*	*
2	380.51	361.02	35452.	0.00	40.00	2123.25	*	2974.	379.80*
	385.00	354.94					*	*	*
3	387.50	351.78	28329.	0.00	40.00	2696.87	*	436.	386.67*
	390.00	348.62					*	*	*
4	392.50	345.59	34194.	0.00	40.00	3083.01	*	0.	0.00*
	395.00	342.57					*	*	*
5	396.01	341.38	15486.	0.00	40.00	3345.83	*	0.	0.00*
	397.03	340.19					*	*	*
6	398.51	338.49	24210.	0.00	35.00	3526.48	*	0.	0.00*
	400.00	336.78					*	*	*
7	402.50	334.00	43366.	0.00	35.00	3806.15	*	0.	0.00*
	405.00	331.23					*	*	*
8	405.36	330.84	6525.	0.00	35.00	4003.85	*	0.	0.00*
	405.73	330.44					*	*	*
9	407.86	328.17	39136.	800.00	25.00	2746.37	*	0.	0.00*
	410.00	325.90					*	*	*
10	412.17	323.68	40576.	800.00	25.00	2811.24	*	0.	0.00*
	414.33	321.46					*	*	*
11	414.67	321.12	6358.	800.00	25.00	2847.08	*	0.	0.00*
	415.00	320.79					*	*	*
12	421.83	314.29	140436.	800.00	25.00	3085.62	*	0.	0.00*
	428.65	307.79					*	*	*
13	431.83	304.99	72352.	800.00	25.00	3420.33	*	0.	0.00*
	435.00	302.19					*	*	*
14	437.50	300.08	60891.	800.00	25.00	3653.46	*	0.	0.00*
	440.00	297.96					*	*	*
15	442.50	295.93	65257.	800.00	25.00	3915.44	*	0.	0.00*
	445.00	293.89					*	*	*
16	447.32	292.06	63748.	800.00	25.00	4126.35	*	0.	0.00*
	449.63	290.24					*	*	*
17	449.82	290.10	5127.	0.00	35.00	5754.21	*	0.	0.00*
	450.00	289.96					*	*	*
18	452.50	288.06	70022.	0.00	35.00	5821.42	*	0.	0.00*
	455.00	286.17					*	*	*
19	457.87	284.08	79782.	0.00	35.00	5950.41	*	0.	0.00*
	460.74	281.99					*	*	*
20	462.67	280.49	59318.	500.00	26.00	3477.22	*	0.	0.00*
	465.00	278.99					*	*	*
21	472.89	273.82	222591.	500.00	26.00	3528.02	*	0.	0.00*
	480.77	268.66					*	*	*
22	488.92	263.92	233692.	500.00	26.00	3586.05	*	0.	0.00*
	497.06	259.18					*	*	*
23	505.45	254.87	242113.	500.00	26.00	3610.23	*	0.	0.00*
	513.83	250.56					*	*	*

## S L I C E I N F O R M A T I O N

NO.	X		Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE (PSF)	*BOUNDARY FORCES*	
	LEFT CENTER RIGHT	LEFT CENTER RIGHT						AT SURFACE	
								*****	
								FORCE-LOCATION	
								(LBS)	X
	513.83	250.56						*	*
24	514.42	250.28	16935.	500.00	26.00	3613.47	*	0.	0.00*
	515.00	250.00					*		*
25	523.61	246.17	247695.	2500.00	0.00	0.00	*	0.	0.00*
	532.22	242.33					*		*
26	541.02	238.96	249510.	2500.00	0.00	0.00	*	0.	0.00*
	549.82	235.58					*		*
27	558.79	232.67	248125.	2500.00	0.00	0.00	*	0.	0.00*
	567.75	229.75					*		*
28	576.60	227.38	236737.	2500.00	0.00	0.00	*	0.	0.00*
	585.45	225.00					*		*
29	592.72	223.40	187105.	350.00	28.00	6728.27	*	0.	0.00*
	600.00	221.80					*		*
30	609.29	220.21	230306.	350.00	28.00	6557.69	*	0.	0.00*
	618.58	218.62					*		*
31	627.94	217.52	223530.	350.00	28.00	6369.54	*	0.	0.00*
	637.30	216.42					*		*
32	646.71	215.81	213828.	350.00	28.00	5997.69	*	0.	0.00*
	656.11	215.20					*		*
33	663.06	215.07	149718.	350.00	28.00	5679.40	*	0.	0.00*
	670.00	214.93					*		*
34	679.42	215.18	190295.	350.00	28.00	5347.30	*	0.	0.00*
	688.84	215.43					*		*
35	698.24	216.16	173142.	350.00	28.00	4825.95	*	0.	0.00*
	707.64	216.90					*		*
36	716.98	218.13	153597.	350.00	28.00	4284.97	*	0.	0.00*
	726.33	219.36					*		*
37	735.59	221.08	131900.	350.00	28.00	3685.81	*	0.	0.00*
	744.86	222.80					*		*
38	747.43	223.37	32717.	350.00	28.00	3279.29	*	0.	0.00*
	750.00	223.93					*		*
39	752.28	224.47	27517.	350.00	28.00	3153.35	*	227.	753.04*
	754.55	225.00					*		*
40	763.65	227.45	95029.	2500.00	0.00	0.00	*	5449.	765.68*
	772.76	229.90					*		*
41	781.72	232.83	68724.	2500.00	0.00	0.00	*	12461.	782.56*
	790.68	235.76					*		*
42	799.47	239.15	41321.	2500.00	0.00	0.00	*	19078.	799.99*
	808.26	242.54					*		*
43	816.63	246.27	13235.	2500.00	0.00	0.00	*	24445.	816.98*
	825.00	250.00					*		*
44	825.00	250.00	0.	500.00	26.00	.01	*	2.	825.00*
	825.00	250.00					*		*

## ITERATION INFORMATION

ITER	F	THETA (RADIAN DEGREES)	DELF	DELT (RADIAN)	FORCE IMBAL (LBS.)	MOMENT IMBAL (FT.LBS.)
1	1.1749	.23195	13.290	.0000	.00000	-0.
						-1.

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = 1.175 ( 1 ITERATIONS)

SIDE FORCE INCLINATION = 13.29 DEGREES

SLICE NO.	XAVG	NORMAL STRESS (PSF)	SHEAR STRESS (PSF)	* LINE OF THRUST *	* E-FORCE (LBS) *
				X YT(TOT) FRACTION	
0				365.5 382.8 0.0000	0.
1	370.8	1361.	78.	376.9 374.9 .3744	23657.
2	390.5	2786.	76.	385.0 366.2 .2996	54577.
3	387.5	3794.	784.	390.0 361.4 .2750	74862.
4	392.5	4534.	1036.	395.0 356.7 .2575	97104.
5	396.7	5079.	1237.	397.0 354.9 .2519	106663.
6	398.5	5542.	1201.	400.0 352.2 .2433	122011.
7	402.5	5976.	1293.	405.0 347.8 .2413	148712.
8	405.4	6254.	1341.	405.7 347.2 .2412	152657.
9	407.9	6613.	1977.	410.0 344.2 .2465	171501.
10	412.2	6244.	2043.	414.3 341.2 .2509	190391.
11	414.7	6375.	2081.	415.0 340.7 .2515	193292.
12	421.8	7074.	2264.	428.7 331.5 .2575	254328.
13	431.8	8082.	2531.	435.0 327.4 .2575	283507.
14	437.5	8773.	2713.	440.0 324.1 .2566	307039.
15	442.5	9531.	2910.	445.3 320.9 .2550	331339.
16	447.3	10168.	3079.	449.6 318.0 .2531	354160.
17	449.8	10566.	2868.	450.0 317.8 .2529	356096.
18	452.5	10614.	2856.	455.0 314.6 .2550	382041.
19	457.9	10681.	2819.	460.7 311.2 .2593	410540.
20	462.9	10577.	3373.	465.0 309.0 .2641	427879.
21	472.9	10952.	3507.	480.8 301.3 .2813	485615.
22	488.9	11484.	3704.	497.1 294.2 .2987	534176.
23	505.4	11918.	3874.	513.0 287.8 .3167	571927.
24	514.4	12121.	3957.	515.3 287.4 .3180	574095.
25	523.6	12612.	2128.	532.2 279.6 .3197	634140.
26	541.0	12711.	2128.	549.8 272.7 .3242	682551.
27	558.8	12678.	2128.	567.8 266.6 .3307	718244.
28	576.6	12515.	2128.	585.4 261.3 .3384	740095.
29	592.7	12266.	2804.	600.0 257.9 .3502	738522.
30	609.3	12088.	2801.	618.6 254.2 .3554	724914.
31	627.9	11945.	2848.	637.3 251.1 .3611	697898.
32	646.7	11680.	2869.	656.1 248.7 .3677	658169.
33	663.1	11352.	2865.	670.0 247.3 .3732	621427.
34	679.4	10909.	2833.	688.8 246.0 .3821	562657.
35	698.2	10274.	2764.	707.6 245.3 .3928	495524.
36	717.0	9489.	2653.	726.3 245.2 .4061	422587.
37	735.6	8542.	2496.	744.9 245.0 .4220	346384.
38	747.4	7859.	2370.	750.0 245.7 .4269	325915.
39	752.3	7605.	2312.	754.6 245.9 .4313	307186.
40	763.7	7052.	2128.	772.8 246.6 .4455	232143.
41	781.7	6224.	2128.	790.7 247.6 .4613	153657.
42	799.5	5261.	2128.	808.3 248.8 .4803	74523.
43	816.6	4178.	2128.	825.0 250.2 1.0000	0.

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = 1.175 ( 1 ITERATIONS)

SIDE FORCE INCLINATION = 13.29 DEGREES

SLICE NO.	XAVG	NORMAL STRESS (PSF)	SHEAR STRESS (PSF)	* LINE OF THRUST *	* E-FORCE (LBS) *
				X YT(TOT) FRACTION	
44	825.0	3359.	1820.	825.0 1390.5 0.0000	0.

SEARCH COMPLETED

F1 = 1.174901

THETA1 = 13.289966



EXHIBIT D-3

LOAD SHEETS

LIST OF INPUT DATA AND OUTPUT FOR PROBABILISTIC CASE

INPUT DATA

OUTPUT





## INPUT

0999999999GSS031776 EXAMPLE PROB. B - PIT MINE SLOPE

0.	0.	0.							
3.	3.	0.	0.	4.					
2.	1.								
0.	1250.	1000.	1250.						
2.	2.								
0.	1200.	1000.	1200.						
2.	3.								
0.	1050.	1000.	1050.						
0.	0.	0.	40.	135.				5.	
350.	0.	0.	25.	160.				5.	
400.	0.	0.	30.	160.				5.	
5.									
100.	1000.		4.						
125.	1040.		4.						
270.	1135.		4.						
390.	1210.		4.						
550.	1220.		4.						
1.									
SLOPE 1									
7.									
0.	1000.	100.	1000.	125.	1040.	215.	1200.	275.	1250.
420.	1250.	1000.	1250.						
1.									
2.									
4.	12.								
100.	1000.	200.	1010.	330.	1070.	420.	1200.		
1.	-20.	10.	10.		1.				
100.	3.	3.	50.	.02	1.	1.	1.	1.	
3.	0.	2.	2.	50.	20.				
1.	4.	1.	4.						
1.	5.	1.	15.						
2.	1.	1.	35.						
2.	4.	4.	5.	25.	40.				
2.	5.	1.	15.						
3.	1.	1.	40.						
3.	4.	1.	3.						
3.	5.	1.	20.						
4.	1.	2.	3.	10.	10.	0.	3.		

END

# OUTPUT

```

*****
*
*   PROGRAM GENSAM
*
*   SPENCER'S METHOD OF SLOPE STABILITY ANALYSIS
*
*   FOR GENERALIZED FAILURE SURFACES
*
*   LATEST REVISION - 3/ 1/76
*
*   DATE RUN - 21/C3/77      TIME RUN - 16.22.52.
*
*****

```

0999999999 GSS 031776 EXAMPLE PROB. B - PIT MINE SLOPE

PROFILE	LINE NO.	MATERIAL TYPE	X	Y	COORDINATES X	COORDINATES Y	X	Y
1	1	1	0.00	1250.00	1000.00	1250.00		
2	2	2	0.00	1200.00	1000.00	1200.00		
3	3	3	0.00	1050.00	1000.00	1050.00		

0999999999 GSS 031776 EXAMPLE PROB. B - PIT MINE SLOPE

## M A T E R I A L   D A T A   -   T Y P E   1

```

COHESION (UNDRAINED STRENGTH) - ISOTROPIC
      C      C/Z      REF. HT.
      0.      0.00      0.00      0.00
PHI - - - - - 40.00 DEGREES
UNIT WEIGHT - - - - - 135.00 PCF
PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE
UNIT WEIGHT OF WATER - - - - 62.40 PCF

```

## M A T E R I A L   D A T A   -   T Y P E   2

```

COHESION (UNDRAINED STRENGTH) - ISOTROPIC
      C      C/Z      REF. HT.
      0.      350.00      0.00      0.00
PHI - - - - - 25.00 DEGREES
UNIT WEIGHT - - - - - 160.00 PCF
PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE
UNIT WEIGHT OF WATER - - - - 62.40 PCF

```

## M A T E R I A L   D A T A   -   T Y P E   3

```

COHESION (UNDRAINED STRENGTH) - ISOTROPIC
      C      C/Z      REF. HT.
      0.      400.00      0.00      0.00
PHI - - - - - 30.00 DEGREES
UNIT WEIGHT - - - - - 160.00 PCF
PORE PRESSURES DETERMINED FROM PIEZOMETRIC LINE
UNIT WEIGHT OF WATER - - - - 62.40 PCF

```

0999999999 GSS 031776 EXAMPLE PROB. B - PIT MINE SLOPE

PIEZOMETRIC ELEVATION DATA - NPIEZ = 4

	X	Y
1	100.00	1000.00
2	125.00	1040.00
3	270.00	1135.00
4	390.00	1210.00
5	550.00	1220.00

1 SLOPE(S) ANALYZED FOR SOIL PROFILE TITLED -

0999999999 GSS 031776 EXAMPLE PROB. B - PIT MINE SLOPE

KEEP1 = 0 KEEP2 = 0 KEEP3 = 0

SLOPE DESIGNATION -

SLOPE 1  
SLOPE POINTS  
X Y  
0.00 1000.00  
1000.00 1250.00

1 SHEAR SURFACE(S) OR SEARCH(ES) CONSIDERED

SLOPE 1

SPECIFIED SHEAR SURFACE COORDINATES

I	X	Y
1	100.00	1000.00
2	200.00	1010.00
3	330.00	1070.00
4	420.00	1200.00

ASSUMED DEPTH OF WATER IN TENSION CRACK - - - - -	12.00 FT
UNIT WEIGHT OF WATER - - - - -	62.40 PCF
INITIAL ASSUMED VALUE FOR FACTOR OF SAFETY - - - - -	1.00
INITIAL ASSUMED VALUE FOR SIDE FORCE INCLINATION - - - -	-20.00 DEGREES
ITERATION LIMIT - - - - -	20
ALLOWED FORCE IMBALANCE SPECIFIED - - - - -	10.00 LBS.
ALLOWED MOMENT IMBALANCE SPECIFIED - - - - -	10.00 FT-LBS.

SHEAR SURFACE COORDINATES

I	X	Y
1	100.00	1000.00
2	125.00	1002.50
3	130.63	1003.06
4	200.00	1010.00
5	215.00	1016.92
6	270.00	1042.31
7	275.00	1044.62
8	286.67	1050.00
9	330.00	1070.00
10	390.00	1156.67
11	420.00	1200.00

.031 SECONDS REQUIRED IN GENER2

.010 SECONDS REQUIRED IN SSDATA

## S L I C E I N F O R M A T I O N

NO.	X	Y	WEIGHT (LBS/FT)	COHESION (PSF)	FRICTION ANGLE (DEGS)	PORE PRESSURE* (PSF)	*BOUNDARY FORCES* AT SURFACE	
	LEFT CENTER RIGHT	LEFT CENTER RIGHT					* FORCE-LOCATION*	
							(LBS)	X
	100.00	1300.00						
1	112.50	1001.25	75000.	400.00	30.00	1170.00	0.	0.00*
	125.00	1002.50						
2	127.81	1002.78	37997.	400.00	30.00	2437.43	0.	0.00*
	139.63	1003.06						
3	165.31	1006.53	1167003.	400.00	30.00	3736.54	0.	0.00*
	200.00	1010.00						
4	207.50	1013.46	415692.	400.00	30.00	5028.83	0.	0.00*
	215.00	1016.92						
5	242.50	1029.62	1669541.	400.00	30.00	5451.72	0.	0.00*
	270.00	1042.31						
6	272.50	1043.46	157575.	400.00	30.00	5869.50	0.	0.00*
	275.00	1044.62						
7	280.63	1047.31	363776.	400.00	30.00	5894.50	0.	0.00*
	286.67	1050.00						
8	308.33	1060.00	1263167.	350.00	25.00	6175.00	0.	0.00*
	330.00	1070.00						
9	360.00	1113.33	1237000.	350.00	25.00	4862.00	0.	0.00*
	390.00	1156.67						
10	405.00	1178.33	306500.	350.00	25.00	2034.50	0.	0.00*
	420.00	1200.00						

## ITERATION INFORMATION

ITER	F	THETA (RAOIANIS DEGREES)	DELTA (RADIANS)	DELTA (RADIANS)	FORCE IMBAL (LBS.)	MOMENT IMBAL (FT.LBS.)
1	1.0000	-.34907	-20.000	.1621 .1217 .1208 .1208	-.11294 -.17592 -.17453 -.17453	506583. SECOND ORDER CORRECTION FACTORED VALUES ADJUSTED VALUES
2	.8792	-.52360	-30.000	-.0091 -.0091 -.0091	-.00614 -.00592 -.00592	-25165. SECOND ORDER CORRECTION SECOND ORDER CORRECTION
3	.8883	-.52952	-30.339	.0000 .0000	-.00000 -.00000	2. SECOND ORDER CORRECTION
4	.8883	-.52952	-30.339	-.0000	-.00000	-0. 0.

.046 SECONDS REQUIRED IN CALCFS

## S O L U T I O N I N F O R M A T I O N

FACTOR OF SAFETY = .888 ( 4 ITERATIONS)

SIDE FORCE INCLINATION = -30.34 DEGREES

Slice NO.	XAVG	NORMAL STRESS (PSF)	SHEAR STRESS (PSF)	* LINE OF THRUST *			E-FORCE (LBS)
				*****			
				X	YT(TOT)	FRACTION	
0				100.0	1000.0	0.0000	0.
1	112.5	3834.	2182.	125.0	1008.6	.1618	44961.
2	127.8	8349.	4293.	130.6	1009.6	.1396	64410.
3	165.3	21344.	11894.	200.0	1028.9	.1155	741458.
4	297.5	23001.	12130.	215.0	1037.1	.1100	764179.
5	242.5	25193.	13281.	270.0	1066.7	.1201	855088.
6	272.5	26144.	13666.	275.0	1069.4	.1209	863085.
7	280.8	25857.	13424.	286.7	1075.8	.1288	880471.
8	308.3	23895.	9695.	330.0	1103.1	.1840	822709.
9	360.0	9785.	2978.	390.0	1170.3	.1461	153345.
10	405.0	4663.	1774.	420.0	1204.0	.0800	4493.

.030 SECONDS REQUIRED IN FINAL

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PROBABILITY INPUT DATA

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CONTROL VALUES

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PROBABILITY ANALYSIS OPTION FLAG 1  
 NUMBER OF ANALYSES TO BE PERFORMED 100  
 RANDOM NUMBER SEED 3  
 PRINT OPTION 3  
 WIDTH OF GRAPH ACROSS THE PAGE 50  
 CLASS SIZE OR NUMBER OF CLASSES .02  
 SAFETY FACTOR BELOW WHICH SLOPE WILL FAIL 1.00  
 SOIL PROFILE LINE INPUT OPTION FLAG 1  
 MATERIAL INPUT OPTION FLAG 1  
 PRESSURE AND PIEZOMETRIC INPUT OPTION FLAG 1

-----

SOIL PROFILE LINE INPUT DATA

-----

SOIL LINE NUMBER	NUMBER OF POINTS	X AND/OR Y	IND. OR TOGETHER	DISTRIBUTION	ST1	ST2	ST3	POINT NUMBERS
3	2 (ALL)	ONLY Y	TOGETHER	2-TRIANGULAR	50.00	20.00	-0.00	1 2

-----

MATERIAL INPUT DATA

-----

MATERIAL TYPE	VARIABLE NUMBER	DISTRIBUTION	ST1	ST2	ST3
1	4-PHI	1-GAUSSIAN	4.00	-0.00	-0.00
1	5-GAMMA	1-GAUSSIAN	15.00	-0.00	-0.00
2	1-C	1-GAUSSIAN	35.00	-0.00	-0.00
2	4-PHI	4-TRUNCATED GAUSSIAN	5.00	25.00	40.00
2	5-GAMMA	1-GAUSSIAN	15.00	-0.00	-0.00
3	1-C	1-GAUSSIAN	40.00	-0.00	-0.00
3	4-PHI	1-GAUSSIAN	3.00	-0.00	-0.00
3	5-GAMMA	1-GAUSSIAN	20.00	-0.00	-0.00

-----

PRESSURE AND PIEZOMETRIC INPUT DATA

-----

MTYPE	NUMBER OF POINTS	X AND/OR Y	IND. OR TOGETHER	DISTRIBUTION	ST1	ST2	ST3	POINT NUMBERS
4-PIEZOMETRIC	1	ONLY Y	TOGETHER	3-UNIFORM	10.00	10.00	0.00	3

=====

DETAILS OF ANALYSIS

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=====

SAMPLE NUMBER 1

=====

SOIL PROFILE LINE VALUES

-----

LINE NUMBER	TYPE	X	Y	X	Y	X	Y	X	Y	X	Y
1	1	0.00	1250.00	10.00	1250.00						
2	2	0.00	1200.00	1250.00	1400.00						
3	3	0.00	1040.00	1050.00	1640.00						

MATERIAL VALUES

-----

MATERIAL TYPE	C	C/2	REF. HT.	PHI	GAMMA	RU	X00LP	KEY	K1
1	0.00	0.00	0.00	42.40	123.00	-1.00	0	0	0
2	300.00	0.00	0.00	36.35	144.12	-1.00	0	0	0
3	300.00	0.00	0.00	36.35	144.12	-1.00	0	0	0

PIEZOMETRIC LINE VALUES

-----

POINT NUMBER	X	Y	NPICZ
1	100.00	1000.00	
2	125.00	1040.00	
3	270.00	1120.00	
4	300.00	1210.00	
5	550.00	1220.00	

FORCE IMBALANCE = .00      MOMENT IMBALANCE = .00  
 NUMBER OF ITERATIONS = 4      SIDE FORCE INCLINATION = -30.56      FACTOR OF SAFETY = .92

=====

SAMPLE NUMBER 2

=====

SOIL PROFILE LINE VALUES

-----

LINE NUMBER	TYPE	X	Y	X	Y	X	Y	X	Y	X	Y
1	1	0.00	1250.00	1000.00	1250.00						
2	2	0.00	1200.00	1250.00	1250.00						
3	3	0.00	1050.00	1000.00	1050.00						

MATERIAL VALUES

-----

MATERIAL TYPE	C	C/2	REF. HT.	PHI	GAMMA	RU	X00LP	KEY	K1
1	0.00	0.00	0.00	42.40	123.00	-1.00	0	0	0
2	350.00	0.00	0.00	36.35	144.12	-1.00	0	0	0
3	350.00	0.00	0.00	36.35	144.12	-1.00	0	0	0

PIEZOMETRIC LINE VALUES

-----

POINT NUMBER	X	Y	NPICZ
1	110.00	1050.00	
2	125.00	1040.00	
3	270.00	1130.00	
4	300.00	1210.00	
5	550.00	1220.00	

FORCE IMBALANCE = 0.00      MOMENT IMBALANCE = -30.62  
 NUMBER OF ITERATIONS = 4      SIDE FORCE INCLINATION = -30.62      FACTOR OF SAFETY = .99

=====

SAMPLE NUMBER 3

SOIL PROFILE LINE VALUES

-----

LINE NUMBER	MATERIAL TYPE	X	Y	X	Y	X	Y	X	Y	X	Y
1	1	0.00	1250.00	1000.00	1250.00						
2	2	0.00	1200.00	1000.00	1200.00						
3	3	0.00	1061.42	1000.00	1061.42						

MATERIAL VALUES

-----

MATERIAL TYPE	C	C/Z	REF. HT.	PHI	GAMMA	RU	KODEP	KEY	KI
1	0.00	0.00	0.00	48.50	130.21	-0.00	5	0	0
2	358.69	0.00	0.00	21.37	165.22	-0.00	5	0	0
3	336.93	0.00	0.00	30.32	119.23	-0.00	5	0	0

PIEZOMETRIC LINE VALUES

-----

POINT NUMBER	X	Y	NPIEZ
1	100.00	1000.00	4
2	125.00	1040.00	4
3	270.00	1131.89	4
4	390.00	1210.00	4
5	550.00	1220.00	4

FORCE IMBALANCE = -0.00      MOMENT IMBALANCE = -0.00  
 NUMBER OF ITERATIONS = 4      SIDE FORCE INCLINATION = -31.28      FACTOR OF SAFETY = .86

=====

SAMPLE NUMBER 99

SOIL PROFILE LINE VALUES

-----

LINE NUMBER	MATERIAL TYPE	X	Y	X	Y	X	Y	X	Y	X	Y
1	1	0.00	1250.00	1000.00	1250.00						
2	2	0.00	1200.00	1000.00	1200.00						
3	3	0.00	1050.15	1000.00	1050.15						

MATERIAL VALUES

-----

MATERIAL TYPE	C	C/Z	REF. HT.	PHI	GAMMA	RU	KODEP	KEY	KI
1	0.00	0.00	0.00	45.21	135.33	-0.00	5	0	0
2	376.06	0.00	0.00	22.87	173.59	-0.00	5	0	0
3	387.88	0.00	0.00	27.86	179.57	-0.00	5	0	0

PIEZOMETRIC LINE VALUES

-----

POINT NUMBER	X	Y	NPIEZ
1	100.00	1000.00	4
2	125.00	1040.00	4
3	270.00	1132.43	4
4	390.00	1210.00	4
5	550.00	1220.00	4

FORCE IMBALANCE = -0.00      MOMENT IMBALANCE = -0.00  
 NUMBER OF ITERATIONS = 4      SIDE FORCE INCLINATION = -30.18      FACTOR OF SAFETY = .84

=====

SAMPLE NUMBER 100

SOIL PROFILE LINE VALUES

-----

LINE NUMBER	MATERIAL TYPE	X	Y	X	Y	X	Y	X	Y	X	Y
1	1	0.00	1250.00	1000.00	1250.00						
2	2	0.00	1200.00	1000.00	1200.00						
3	3	0.00	1057.17	1000.00	1057.17						

MATERIAL VALUES

-----

MATERIAL TYPE	C	C/Z	REF. HT.	PHI	GAMMA	RU	KODEP	KEY	KI
1	0.00	0.00	0.00	35.24	145.71	-0.00	5	0	0
2	403.42	0.00	0.00	26.40	163.84	-0.00	5	0	0
3	419.61	0.00	0.00	34.66	153.35	-0.00	5	0	0

PIEZOMETRIC LINE VALUES

-----

POINT NUMBER	X	Y	NPIEZ
1	100.00	1000.00	4
2	125.00	1040.00	4
3	270.00	1137.92	4
4	390.00	1210.00	4
5	550.00	1220.00	4

FORCE IMBALANCE = -0.00      MOMENT IMBALANCE = -0.00  
 NUMBER OF ITERATIONS = 4      SIDE FORCE INCLINATION = -30.72      FACTOR OF SAFETY = 1.04

=====

MIN F.S.= .68867 MAX F.S.= 1.06675

FREQUENCY DISTRIBUTION OF FACTOR OF SAFETY VALUES

CLASS	INTERVAL	FREQUENCY						FRQ	PCT
		0	10	20	30	40	50		
1	.68	.70	.X					1	1.0
2	.70	.72	.X					1	1.0
3	.72	.74	.X					1	1.0
4	.74	.76	.XXX					3	3.0
5	.76	.78	.XXXX					4	4.0
6	.78	.80	.XXXX					4	4.0
7	.80	.82	.XXXXXXXX					8	8.0
8	.82	.84	.XXXXXXXX					8	8.0
9	.84	.86	.XXXXXXXXXXXX					13	13.0
10	.86	.88	.XXXXXXXXXXXX					13	13.0
11	.88	.90	.XXXXXXXXXX					9	9.0
12	.90	.92	.XXXXXXXX					8	8.0
13	.92	.94	.XXXX					4	4.0
14	.94	.96	.XXXX					4	4.0
15	.96	.98	.XXXXXX					6	6.0
16	.98	1.00	.XXXXX					5	5.0
17	1.00	1.02	.XXXX					4	4.0
18	1.02	1.04	.X					1	1.0
19	1.04	1.06	.XX					2	2.0
20	1.06	1.08	.X					1	1.0

## SAMPLE STATISTICS

MEAN= .879      S.D.= .079      SKEWNESS= .053      KURTOSIS= 2.69      SAMPLE SIZE= 100

### PROBABILITY OF FAILURE

```

P.F.= 93.77 %   BASED ON SAMPLE OF KINEMATICALLY VALID CASES AND ASSUMING THAT IT IS
                NORMAL WITH MEAN = .879 AND STD. DEV. = .079
P.F.= 92.00 %   BY COUNT WHERE KINEMATICALLY IMPOSSIBLE CASES ARE CONSIDERED TO BE SAFE
                ***NUMBER OF SUCH CASES WERE      0

```

```

=====
= PROGRAM GENSAM =
= SPENCER AND WRIGHT SLOPE STABILITY ANALYSIS =
= INPUT DATA SHEET =
=====

```

NOTES: 1. ALL CARDS EXCEPT A AND J HAVE 8 COLUMNS/FIELD AND UP TO 10 FIELDS/CARD BEGINNING IN COLUMNS 1, 9, 17, 25, 33, 41, 49, 57, 65, AND 73. THE FIELDS IN CARD A BEGIN IN COLUMNS 1, 11, 14, AND 21. CARD J CONTAINS ONLY 1 FIELD WHICH BEGINS IN COLUMN 1.  
2. ALL NUMERIC VALUES EXCEPT JOBNO AND IDATE MUST CONTAIN A DECIMAL POINT.

## A. HEADER DATA

```

JOBNO   INI IDATE   IHEAD
09999999 0001031770  EXAMPLE PROB. 8 - PIT MINE SLOPE

```

## B. OUTPUT CONTROL DATA

```

ISUP    ISUP1    ISUP2
0.      0.      0.

```

## C. SOIL PROFILE DATA

```

NP      NHA15    MBPL1    MBPL2    NPIEZ    UWW    KEEP1    KEEP2    KEEP3
03.     03.     0.      0.      14.     1.      1.      1.      1.

```

## D. PROFILE LINE CONTROL DATA

```

NPP      MATYPE
12.      11.

```

## E. PROFILE LINE COORDINATE DATA POINTS

```

XP      YP      XP      YP      XP      YP      XP      YP      XP      YP
0.      1250.   1000.   1250.   1.      1.      1.      1.      1.      1.

```

REPEAT OF LINES D AND E FOR ADDITIONAL PROFILE LINES

```

NPP      MATYPE
12.      12.

XP      YP      XP      YP      XP      YP      XP      YP      XP      YP
0.      1200.   1000.   1200.   1.      1.      1.      1.      1.      1.

NPP      MATYPE
12.      13.

XP      YP      XP      YP      XP      YP      XP      YP      XP      YP
0.      1050.   1000.   1050.   1.      1.      1.      1.      1.      1.

NPP      MATYPE
1.      1.

XP      YP      XP      YP      XP      YP      XP      YP      XP      YP
1.      1.      1.      1.      1.      1.      1.      1.      1.      1.

NPP      MATYPE
1.      1.

XP      YP      XP      YP      XP      YP      XP      YP      XP      YP
1.      1.      1.      1.      1.      1.      1.      1.      1.      1.

```



[illegible]

#### G. NUMBER OF PRESSURE DATA POINTS

15.

[illegible][illegible]

1/.

## J.SLOPE TITLE

STITLE  
| SLOPE 1 |

## K.NUMBER OF SLOPE COORDINATES

NSP      KEEP4  
| 7.      |

## L.SLOPE COORDINATE DATA POINTS

XS	YS	XS	YS	XS	YS	XS	YS	XS	YS
0.	1000.	100.	1000.	125.	1040.	215.	1200.	275.	1250.
420.	1250.	1000.	1250.						

## M.NUMBER OF ANALYSES

NSTART  
| 1. |

## N.ANALYSIS OPTION DATA

ITYPS  
| 2. |

## O.INDIVIDUAL CIRCLE DATA (ITYPS=1.)

XC	YC	R	THETA	ARCMAX	XFIX	YFIX
DTC	DWATER					

## P.NONCIRCULAR SHEAR SURFACE DATA (ITYPS=2.)

NCORDS	DWATER								
4.	12.								
X	Y	X	Y	X	Y	X	Y	X	Y
100.	1000.	200.	1010.	330.	1070.	420.	1200.		

## Q.AUTOMATIC SEARCH DATA - CIRCULAR SURFACES (ITYPS=3.)

XG	YG	ROCKLN	XFIX	YFIX	ROCK	ACC	TIMEL
ICIRCL	THETA	ARCMAX	OTC	DWATER			

FZ	THETAZ	FLIMIT	TLIMIT	ITERL	MONT
1/.	1-20.	1/0.	1/0.	1	1/.

```

MONT=0. OR 2. - RETURN TO LINE N FOR EACH ANALYSIS (TO NSTART)
                RETURN TO LINE J FOR EACH SLOPE (TO NSLOPS)
                RETURN TO LINE A FOR NEW ANALYSIS

```

END  
| END |

PAGE 8

```
=====
= MONTE CARLO INPUT DATA SHEET =
=====
```

NSAMPL	MF	MPRT	NX	BINSIZ	FC	ISOIL	IMATR	IPRES
100.	3.	3.	50.	1.02	1.	1.	1.	1.

[illegible]

BLANK CARD TERMINATES THIS DATA SET

## CC. MATERIAL DATA

I	J	MDIST	MST1	MST2	MST3
1.	4.	1.	4.		
1.	5.	1.	15.		
2.	1.	1.	35.		
2.	4.	4.	5.	25.	40.
2.	5.	1.	15.		
3.	1.	1.	40.		
3.	4.	1.	3.		
3.	5.	1.	20.		

BLANK CARD TERMINATES THIS DATA SET

## DD. PRESSURE AND PIEZOMETRIC DATA

IAPRE	IBPRE	ICPRE	PDIST	PST1	PST2	PST3	NPTPRE	NPTPRE	NPTPRE
4.	1.	2.	3.	10.	10.	0.	3.		

BLANK CARD TERMINATES THIS DATA SET

## REFERENCES

D-1. Spencer, E. "A method of analysis of the stability of embankments assuming parallel inter-slice forces"; *Geotechnique*; v. 17, pp 11-26; 1967.

D-2. Wright, S.G. "A study of slope stability and the undrained shear strength of clay shales"; Ph.D. thesis; Univ. of California, Berkeley; 1969.

D-3 Duncan, J.M. Unpublished report; Univ. of California, Berkeley; 1975.



## APPENDIX E

### PROGRAM DOCUMENTATION OF MONTEC

(Monte Carlo overlay)





## ABSTRACT

These subroutines perform random sampling, evaluate statistical parameters and plot the results of a probabilistic analysis using stochastic simulation (Monte Carlo analysis). The package has been applied to four programs used for evaluating the probability of sliding of rock slopes.

## PROGRAM IDENTIFICATION

Program title: Monte Carlo Overlay

Code name: MONTEC

Writer: H-S. Kim with modifications by A. Bealer

Organization: Dames & Moore

Date: November, 1974

Updates: September, 1975

Source Language: Fortran IV

Availability: Mining Research Laboratories,  
CANMET, Department of Energy, Mines and Resources,  
555 Booth St, Ottawa, Canada, K1A 0G1

## INTRODUCTION

1. A package of Monte Carlo overlay subroutines has been developed to perform random sampling, evaluate statistical parameters and plot results for probabilistic analysis using stochastic simulation (Monte Carlo analysis).

2. This package is incorporated into the rock slope stability analysis programs for plane, step path, 3-d-wedge, general slip surface and two-block instability modes. For convenience, the

subroutines are documented in this appendix and not separately with each of the stability analysis programs to which they belong.

3. This documentation is intended principally for those involved either in the operation and modification of existing slope stability routines or in the development of new programs which will use the overlay. The Monte Carlo process is described in mathematical terms.

## ENGINEERING DOCUMENTATION

### Description

4. The objective of the Monte Carlo overlay is to find the distribution of a statistical variate,  $t$ , which is dependent on other statistical variates,  $X_1, X_2, X_3, \dots, X_n$ , in a deterministic (non-statistical) way. Hence, given

$$t = T(X_1, X_2, X_3, \dots, X_n)$$

where  $T$  is a deterministic function, and given the

probability laws (distributions),  $P(X)$  of  $X_1, X_2, X_3, \dots, X_n$ , the overlay determines the distribution,  $P(t)$ , of  $t$ , from which statistical information concerning  $t$ , such as mean, standard deviation, etc, can be determined. In the slope stability programs,  $t$  corresponds to the factor of safety or stability factor,  $T$  is the set of equations from which the safety factor is calculated, and  $X_1, X_2, X_3, \dots, X_n$  are the input variables used in the stability calculation.

5. Mathematically, the transformation of  $P(X)$  to  $P(t)$  is the integral on the sample space of  $X_1, X_2, X_3, \dots, X_n$ . The closed form analytical evaluation of this integral in  $n$  dimensions is difficult even if  $T$  is a relatively simple function. Approximations do not provide a universal algorithm independent of  $T$ , hence each problem must be solved individually. Also,  $T$  is often a set of many statements which, due to their complexity, are not amenable to approximation.

6. These problems can be overcome by using a simulation scheme where random samplings of  $X_1, X_2, X_3, \dots, X_n$  from their defined distributions,  $P(X)$ , are transformed by the deterministic function,  $T$ , to provide a random sampling of  $t$  according to the probability function,  $P(t)$ . This

is illustrated by Fig E-1.

7. The success of this so-called Monte Carlo simulation technique depends on how quickly random sampling of  $X_1, X_2, X_3, \dots, X_n$  can be made and how quickly the deterministic law,  $T$ , can transform  $X_1, X_2, X_3, \dots, X_n$  to  $t$ . Computers enable both sampling and transformation to be performed rapidly.

8. The Monte Carlo overlay gives a simulation of  $P(t)$ . The driving routine, MONTE, provides a link between the program which considers the deterministic law,  $T$ , (for example, the program for determining the factor of safety of a slope) and the other subroutines in the overlay package which perform sampling of  $X_1, X_2, X_3, \dots, X_n$ . The results from the deterministic law are used to

**MONTE CARLO PROCEDURE  
(REPEAT N TIMES)**

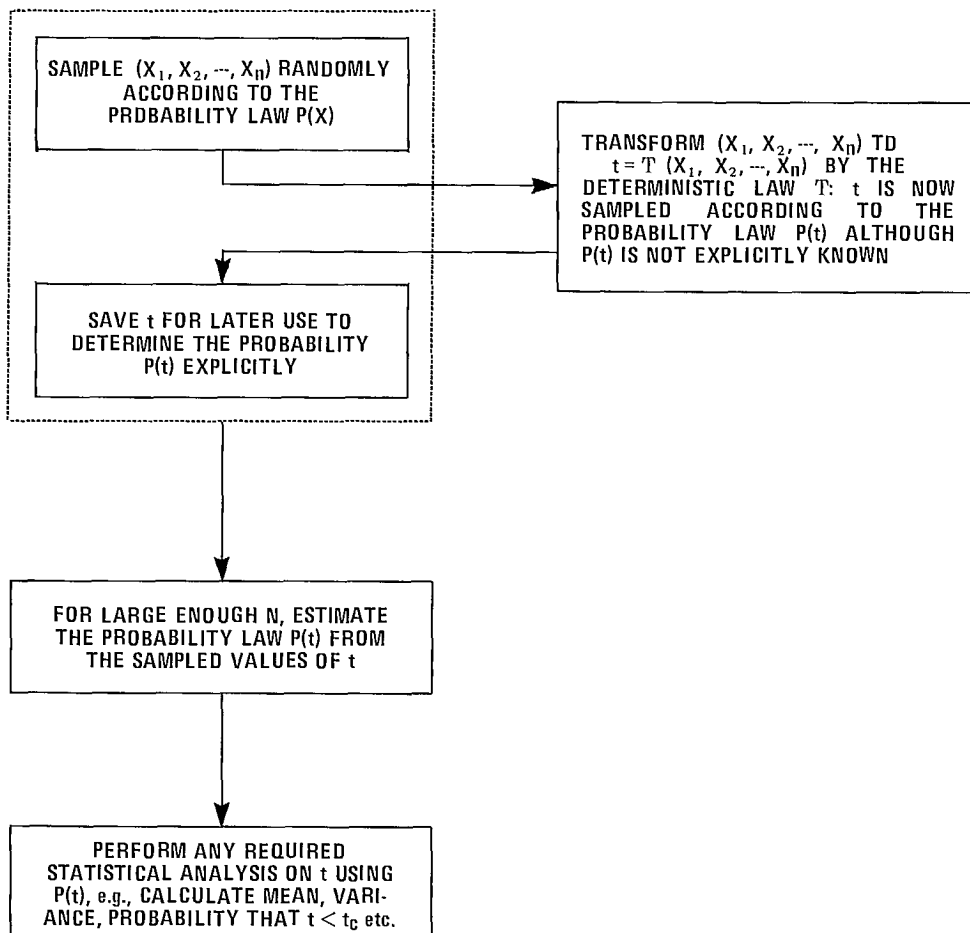


Fig E-1 - The Monte Carlo procedure.

construct a sampled density function for the outcomes of  $t$ . An ideogram plot is used to represent the frequency of occurrence of factors of safety. The y-axis is divided into the number of class intervals specified on input while the number of calculated factors of safety which lie in each class interval are represented by print characters in the x-direction.

#### Method of Solution

9. The Monte Carlo overlay consists of a number of subroutines which are related in the manner shown by the flow chart of Fig E-2.

#### MONTE

10. The exact structure of this subroutine is dependent on the program to which it is attached.

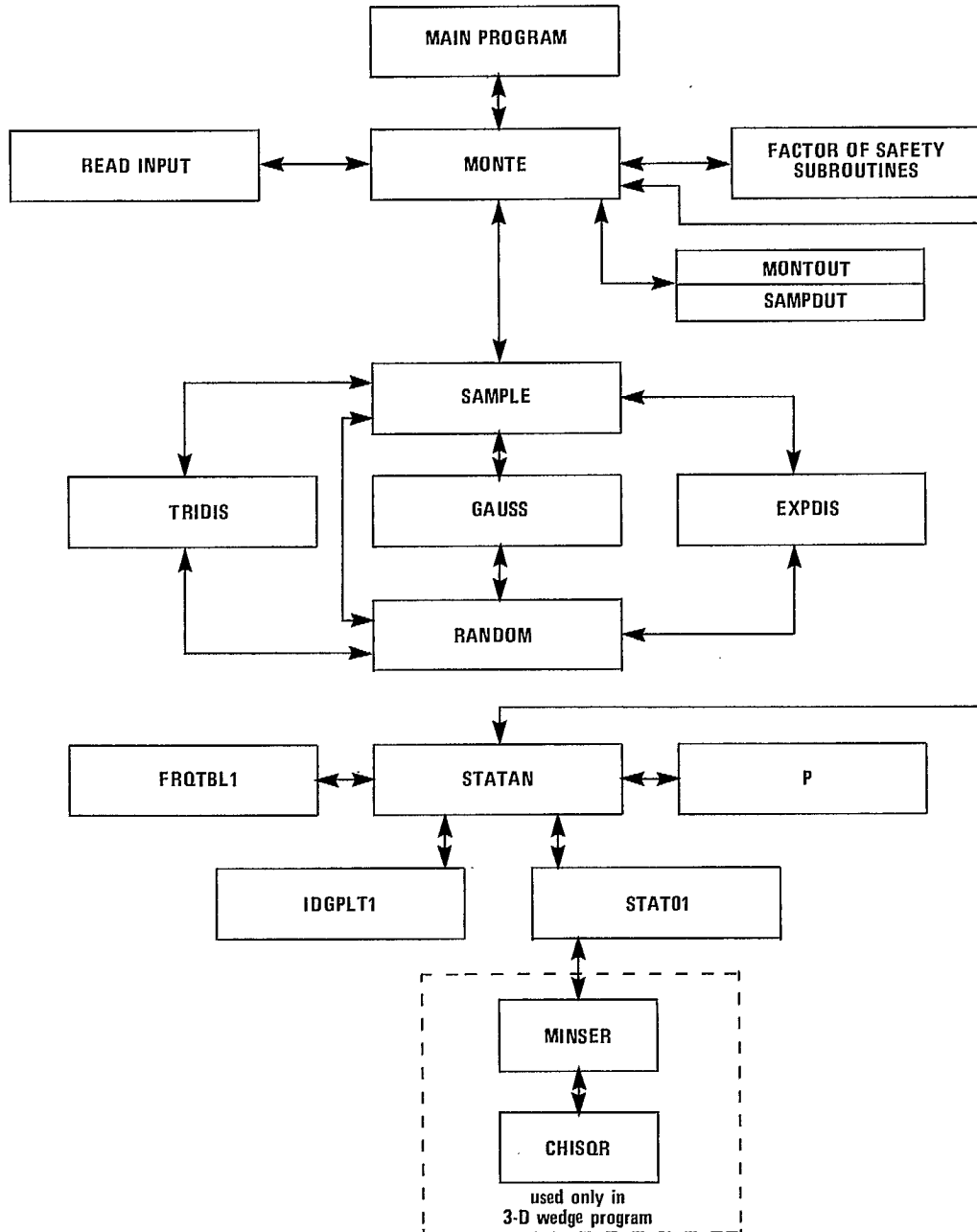


Fig E-2 - Flow chart for Monte Carlo overlay.

It should perform the following functions:

- a. save original values of variables,
- b. read data on variables to be sampled, including distribution parameters,
- c. call SAMPLE routine for each variable to be sampled,
- d. check for case where sliding is kinematically impossible,
- e. calculate and store factor of safety with sampled values,
- f. repeat c. to e. as many times as required,
- g. call STATAN to perform statistical analyses,
- h. replace original values,
- i. return control to main program.

#### SAMPLE

11. This subroutine performs specific sampling tasks or assigns these tasks to the appropriate sampling subroutines. Branching control to all sampling routines should be included in SAMPLE. Currently, six types of distribution are included in the Monte Carlo overlay. These are:

- a. normal (gaussian) distribution with mean,  $\mu$ , and standard deviation,  $\sigma$ , sampled by GAUSS,
- b. triangular distribution over the range (A,B) with mode M, sampled by TRIDIS,
- c. uniform distribution over the range (A,B) sampled in SAMPLE,
- d. truncated normal distribution (A,B), sampled by SAMPLE with GAUSS,
- e. exponential distribution with mean M sampled by EXPDIS,
- f. histogram distribution with up to 9 equal class widths, sampled by HISTO,

12. For the uniform distribution, the sampled value is defined as:

$$S = X(A+B) - A + AV$$

where:

S = sampled value

X = a random number between 0 and 1

AV = the mean value, assumed as the basic data value

A = distance to the lower bound of the variate from AV

B = distance to the upper bound of the variate from AV.

13. Descriptions of methods of sampling from the normal, triangular, exponential and histogram distributions are given in subroutines GAUSS, TRIDIS, EXPDIS and HISTO respectively.

14. The CALL statement should be similar to the following example:

```
CALL SAMPLE (MF, ITYPE, AV, ST1, ST2, ST3, ST4,
             VAL)
```

where:

MF = seed for the pseudo-random number generator and can be any positive integer. A new number will be returned for use in the next sample (see subroutine RANDOM).

ITYPE = type of distribution to be sampled:

1. - normal, 2. - triangular,
3. - uniform, 4. - truncated normal,
5. - exponential, 6. - histogram.

AV = average, modal or base value of the sampled random variable.

ST1 = represents different variables according to the type of the distribution as follows:

- |                    |  |
|--------------------|--|
| ITYPE = 1. or 4. - | ST1 = standard deviation                   |
| ITYPE = 2. or 3. - | ST1 = lower bound for the range of variate |
| ITYPE = 5. -       | ST1 = decay constant                       |
| ITYPE = 6. -       | ST1 = lowest value of histogram range.     |

ST2 = has the following meaning for distributions specified by ITYPE:

- |                    |  |
|--------------------|--|
| ITYPE = 1. -       | ST2 is not used                                    |
| ITYPE = 2. or 3. - | ST2 = upper bound for the range of the variate     |
| ITYPE = 4. -       | ST2 = lower bound of the range of the distribution |

ITYPE = 5. - ST2 = lower bound of the distribution

ITYPE = 6. - ST2 = class interval of histogram.

ST3 = the upper limit of the distribution for ITYPE = 4. or ITYPE = 5. It is not used for any other distribution.

ST4 = is an array of relative frequencies in the histogram for up to 9 classes.

VAL = sampled value to be returned.

### RANDOM

15. This routine is a pseudo-random generator which uses the congruence method. It exploits the word size of CDC equipment. For details of the method refer to E-1.

16. Pseudo-random number generators are routinely available in all system libraries. These can replace RANDOM since the nature of the simulation requires neither lengthy random number sequences nor fine sensitivity on serial correlation or any other properties.

17. The congruence method used is as follows:

If  $M_{n+1} = p M_n \pmod{t}$

where  $p$  and  $t$  are appropriately chosen integers, and sequence  $(M_n)$  is random with a starting odd integer  $M_0$ , then  $X = M_n/(t+1)$  is a random variate with uniform distribution over  $(0,1)$ . This routine should be called as follows:

CALL RANDOM (M,X)

where:

M = an odd integer argument to be given once at the beginning of sampling

X = sampled random variate having uniform distribution over  $(0,1)$ .

### GAUSS

18. This subroutine uses the central limit theorem to sample a random variable with a normal or gaussian distribution. Twelve random variables are sampled from a uniform distribution 0 to 1

using subroutine RANDOM, and the central limit theorem is then used to obtain the normal variate.

19. Consider  $n$  independent and identically distributed random variables,  $X_1, X_2, \dots, X_n$ , with mean  $\mu$  and variance  $\sigma^2$ . The variate,  $S_n$ , defined as the sum  $(X_1 + X_2 + \dots + X_n)$ , has mean  $n\mu$  and variance  $n\sigma^2$ . By the central limit theorem, the distribution of  $S_n$  approaches the normal distribution with mean  $n\mu$  and variance  $n\sigma^2$  as  $n \rightarrow \infty$ . Equivalently,

$$S'_n = \frac{S_n - n\mu}{\sigma\sqrt{n}}$$

approaches the unit normal distribution as  $n \rightarrow \infty$ . This is the basis for the routine GAUSS, in which  $X$ 's are uniform variates over  $(0,1)$ . Since at  $n=12$ , good convergence is already achieved, this value is taken to be a convenient asymptote for  $n$ . For  $n=12$ ,

$$S'_{12} = S_{12} - 6 = \sum_{r=1}^{12} X_r - 6$$

since  $\mu = 1/2$  and  $\sigma = 1/\sqrt{12}$  for the variate  $X$ . It is clear that the sampling is truncated at six standard deviations each side of the mean. The normal variate,  $V$ , with mean  $m$  and the variance  $S^2$  is then given by

$$V = s.S'_{12} + m$$

The CALL statement is as follows:

CALL GAUSS (M, AV, ST, V)

where:

M = seed for the random number generator,

AV = mean of the distribution being sampled,

ST = standard deviation of the distribution being sampled,

V = sampled value of the Gaussian variate, which is returned to the calling program.

RANDOM is the only subroutine called from GAUSS.

20. Variables used in the source listing of GAUSS are defined as follows:

M = seed for random number generator,  
 SV = mean value of the distribution to be sampled,  
 SD = standard deviation of the distribution to be sampled,  
 V = the sampled value which is returned,  
 A = the sum of 12 uniformly distributed random variables,  
 X = random number chosen in RANDOM.

### TRIDIS

21. This subroutine samples a random variable with a triangular distribution which may be skewed. A random number between 0 and 1, selected by subroutine RANDOM, is used as the fractional area of a unit area triangle. The random variable assumes a value along the base of the input triangle such that the area under the triangle to the left of the assigned value of the random variable is equal to the random number chosen.

22. The area under the unit area triangle from the leftmost point of the base to the modal point of the base is calculated as  $A = EL/(EL + ER)$

where:

EL = length of base from the leftmost point to the modal point,  
 ER = length of base from the modal point to the rightmost point,  
 A = area to left of the mode.

If the random number chosen is less than A

$$X = \sqrt{(R*EL*(EL+ER))} - EL + M$$

where:

R = random number chosen by RANDOM,  
 M = mode,  
 X = the value of the random variable.

If R is greater than A

$$X = ER - \sqrt{(R*ER*(EL+ER))} + M$$

If R=A, X=M.

23. The subroutine can sample from any triangular distribution, skewed or otherwise.

24. The CALL statement for TRIDIS should be as follows:

```
CALL TRIDIS (MF, AV, EL, ER, X)
```

where:

MF = seed for the random number generator,  
 AV = modal value of the triangle,  
 EL = the length of the base to the left of AV,  
 ER = the length of the base to the right of AV,  
 X = the random variable returned.

All input values must be positive.

25. All variables used in TRIDIS are defined in the source listing on comment cards. Subroutines used are RANDOM, which chooses a random number, and SQRT, which is provided by the system to extract the square root of the argument.

### EXPDIS

26. This subroutine samples a deviate from the exponential distributions of type

$$f(x) = N \exp(-X/\lambda)$$

where:

$\lambda$  = decay constant (related to mean),  
 N = normalization constant over the range (A,B) where A and B are positive.

This is done by inverting the cumulative distribution function  $F(X)$  given by

$$F(X) = N \int_0^X e^{-t/\lambda} dt$$

If y is a random deviate uniformly distributed over (0,1), then it can be shown that the desired deviate is

$$X = F^{-1}(y)$$

where:

$$F^{-1} = \text{inverse of } F$$

The CALL statement is as follows:

```
CALL EXPDIS (M, AV, A, B, X)
```

where:

M = seed for the random number sequence,  
 AV = decay constant ( $\lambda$ ),  
 A = lower bound,  
 B = upper bound,  
 X = sampled deviate.

### HISTO

27. This subroutine chooses a value from a distribution defined by a histogram. The input histogram has up to 9 classes of equal width. The relative frequencies for each class are passed to HISTO (they are normalized if necessary to give a cumulative probability of 1.0). The beginning value of the histogram is AH and the width of each class is BH. Thus, if there are N classes ( $N < 9$ ), the maximum histogram value is  $AH + N * BH$ .

28. The cumulative probabilities corresponding to each class limit are formed. Thus the probability of achieving a value less than AH is 0, and the probability of attaining a value less than or equal to  $AH + N * BH$  is 1.

29. A random number is drawn from the uniform range (0., 1.), and the histogram value corresponding to this number is found by interpolating among the cumulative probabilities. This value is returned to the calling program.

30. The call statement for HISTO is

```
CALL HISTO(MF, ST1, ST2, DUM, VAL)
```

where:

MF = seed for the random number generator,  
 ST1 = lowest value for the histogram,  
 ST2 = class interval for the histogram,  
 DUM = is an array of up to 9 values of relative histogram frequencies,  
 VAL = the random variable returned.

HISTO calls subroutine RANDOM which returns a random variable uniformly distributed on (0.,1.).

31. The mean value according to the histogram is calculated and used in probability analysis. This value may differ from the value used in the main program unless the user ensures his histogram data is consistent with the main program data.

### STATAN

32. This subroutine prints an ideogram of calculated factors of safety and performs a statistical analysis of these values giving mean, standard deviation, skewness and kurtosis. Probability of sliding can be determined by count and by assuming a normal distribution for the calculated factors of safety. If kinematically impossible cases are sampled, sliding probability is determined only by direct count and no statistical calculations or plotting is performed. Kinematically impossible cases are counted as safe.

33. STATAN is a driver subroutine for various other subroutines which perform statistical analyses on sampled factors of safety. It is essentially a manipulative subroutine with few calculations. (Note: three slightly different versions, all named STATAN, are used in programs PLAFAM, TWOBAM, WINTAM and GENSAM.)

34. The CALL statement should be of the following form:

```
CALL STATAN (WS, NSAMPL, NPRT, NX, BINSIZ,  
             IMPOS, NPF, PFC, FC)
```

where input values needed are:

WS = array with sampled factor of safety values (see documentation of array "F"),

NSAMPL = number of samples,

MPRT = print code; if greater than or equal to 1. all factor of safety values will be printed,

NX = size of ideogram plot graph - restricted to 100 or less (see documentation on IDGPLT1),

BINSIZ = size of class interval if less than 1. number of classes if greater than or



equal to 1.,

NX = length of ideogram,

PF = probability of sliding determined, assuming normal distribution of outcomes,

PFC = probability of sliding by count,

SAV = average of sampled factors of safety,

SSD = standard deviation of sampled factors of safety,

WS = array containing factors of safety.

### STAT01

38. This subroutine calculates the mean, standard deviation, skewness, and kurtosis of the calculated factors of safety. It is called from subroutine STATAN.

39. Standard deviation is a measure of dispersion from the mean. Skewness is a measure of symmetry about the mean, with zero or near zero values indicating symmetry, negative values indicating left-handed skewness and positive values indicating right-handed skewness. Kurtosis is a measure of peakedness, with high kurtosis indicating more peaked distributions. A normal distribution has a kurtosis of 3.0.

Mean is defined as

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n}$$

where:

$X_i$  = the  $i^{\text{th}}$  factor of safety,

$n$  = number of values,

$\bar{X}$  = mean factor of safety.

Standard deviation ( $s$ ) is defined as

$$s^2 = \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n}$$

Skewness is defined as

$$\alpha_3 = \frac{m(3^{\text{rd}} \text{ moment about the mean})^2}{(2^{\text{nd}} \text{ moment about the mean})^3}$$

IMPOS = number of cases for which factor of safety is not calculated, eg, kinematically impossible cases,

NPF = number of instabilities in sample,

PFC = probability of sliding by count,

FC = critical factor below which a calculated factor of safety designates an instability.

35. All sampled factors of safety can be printed by specifying MPRT greater than or equal to 1. Maximum and minimum values are printed. An ideogram of factors of safety is printed followed by statistical parameters associated with the distribution. Finally, probabilities of sliding by count and assuming a normal distribution of calculated factors of safety are printed.

36. Subroutines and functions called are ABS, which is a system function for determining absolute value, and FRQTBLL, IDGPLT1, STAT01 and P(X), all of which are documented separately.

37. Variables used are defined here in alphabetical order:

B1 = skewness of sample distribution,

B2 = kurtosis of sample distribution,

BINSIZ = class interval size,

CMAx = upper class interval for ideogram,

CMIN = lower class interval for ideogram,

FC = critical value below which factors of safety indicate instability,

FMAx = maximum factor of safety calculated,

FMIN = minimum factor of safety calculated,

IMPOS = number of kinematically impossible cases for which a factor of safety is not calculated,

ISCALE = scale for "X" markers in IDGPLT1,

MAX = intermediate variable for calculating CMAx,

MAXFRQ = maximum frequency in any one class,

MIN = intermediate variable for calculating CMIN,

MPRT = print code,

NBIN = number of classes for ideogram,

NPF = number of instabilities in sample,

NSAMPL = number of sampled values,

where:

m = +1 if the third moment is positive,

-1 if the third moment is negative,

and the  $r^{\text{th}}$  moment about the mean,  $X^r$ , is defined as

$$X^r = \frac{\sum_{i=1}^n (X_i - \bar{X})^r}{n}$$

Kurtosis is defined as

$$\alpha_4 = \frac{4^{\text{th}} \text{ moment about the mean}}{(2^{\text{nd}} \text{ moment about the mean})^2}$$

40. The CALL statement should be of the following form:

```
CALL STAT01 (F,N)
```

where:

F = an array containing factor of safety  
(see documentation of array "F"),

N = number of values in F.

The calling program should have a common block, STAT, as follows:

```
COMMON/STAT/SAV,SSD,B1,B2
```

where:

SAV = average of values in F,

SSD = standard deviation of values in F,

B1 = skewness coefficient of values in F,

B2 = kurtosis coefficient of values in F.

These are the only output values to be returned:

A = sample size,

B1 = skewness of values in SAMPL,

B2 = kurtosis of values in SAMPL,

NSAMPL = sample size,

S = distance from mean ( $X_i - \bar{X}$ ),

SAMPL = array containing factors of safety,

SAV = average of values in SAMPL,

SSD = standard deviation of values in SAMPL,

X1 = sum of values in SAMPL,

X2 = sum of squares of distance from mean,

X3 = sum of cubes of distance from mean,

X4 = sum of fourth powers of distance from mean.

#### FRQTBL1

41. For a specified number of classes or class intervals, FRQTBL1 computes frequencies by per cent and by count and returns the results to the calling program. (Note: a slightly different version, named FRQTBL, is used in WINTAM).

42. The subroutine uses an array (F) consisting of N+2 values for the N calculated factors of safety and the maximum and minimum values. The frequencies computed are returned in array "F".

43. The CALL statement should be of the following form:

```
CALL FRQTBLI (F, N, NBIN, S, MAX)
```

where:

F = an array consisting of N factors of safety followed by the minimum and maximum factors of safety respectively (para 54),

N = number of calculated factors of safety,

NBIN = number of classes in the distribution,

S = size of each class,

MAX = frequency by count in the most populous class (this value is returned, not input)

44. The only subroutine called is the system-contained FLOAT routine. Variables used are defined below in alphabetical order.

BINSIZ = size of each class interval,

F = array for storing calculated factors of safety, minimum and maximum values, frequencies and class boundaries,

H1 = minimum class boundary,

H2 = maximum class boundary,

I = counter for factors of safety,

K = address of frequency by per cent in array "F",  
 K1 = address of class boundary in array "F",  
 MAXFRQ = frequency in most popular class,  
 N = counter for class intervals,  
 NADD = address marker for beginning of frequencies in array "F",  
 NADD1 = address marker for beginning of class boundaries in array "F",  
 NBIN = number of classes,  
 NC = frequency by count of values in each class interval,  
 NSAMPL = number of samples,  
 PC = frequency by per cent of values in each class interval.

#### IDGPLT1

45. This subroutine uses output from FRQTBL1 to print-plot an ideogram of factors of safety with user specified length and number of class intervals.

46. Unit marker is "X" with a scale which is calculated in subroutine STATAN or can be defined by the user if IDGPLT1 is used independently. If the scale is greater than 1, remainders are denoted by a digit in the final column or with a "+" if the remainder is greater than 9.

47. Frequency by per cent and number are printed in the margin of the graph. The graph is of variable height with a maximum of 100 characters. The number of class intervals is also variable.

48. The calling program should have a CALL statement of the following form:

```
CALL IDGPLT1 (F, NX, NY, ISCALE)
```

where:

F = an array with frequency by per cent, and number and boundaries of class intervals; address one in F should correspond to address N + 3 in the documentation of array "F",  
 NX = height of the plot; maximum is 100,

NY = number of class intervals; this corresponds to NBIN,

ISCALE = scale of "X" markers, ie, the frequency represented by each "X" marker on the output plot.

49. The format at execution time for the specified plot height is set using ENCODE. Variables used are defined below in alphabetical order.

B = blank space

BUF = buffer to print "X" markers

BUF1 = buffer to print margin of graph

BUF2 = buffer to print scale values

DIG = array with digits 1 - 9 inclusive in Hollerith form

F = array with frequencies and class boundaries (see documentation on array "F")

FMT = array containing format for printing BUF

FMTBT = array containing format for printing BUF1

FMTTP = array containing format for printing BUF2

H1 = lower class boundary

H2 = upper class boundary

I = index for various do-loops

ISCALE = numeric value of each "X" marker

J = index for filling BUF2

K = address for location of frequencies in array "F"

N = address for class boundaries in array "F"

NC = frequency by count of values in each class interval

NP = number of "X" markers for filling array BUF

NP1 = NP + 1 for use in filling BUF

NR = remaining frequency in last column plotted

NX = length of graph

NX1 = NX + 1 = length of graph with margin

NY = number of class intervals

O = 0 in the Hollerith form

P = period (.) in Hollerith form

PC = percentage frequency of values in each class interval  
 PLUS = plus sign (+) in Hollerith form  
 PT = "I" for marking each tenth place on the graph scale in Hollerith form  
 X = "X" marker in Hollerith form

### P(X)

50. This function calculates the integral from minus infinity to X of a normal curve with mean 0 and variance 1. The absolute error is less than  $1.5 \times 10^{-7}$  for all X.

51. The integral is calculated using a polynomial expansion of P(X). Z(Y) approximates the integral from Y to positive infinity for Y > 0

where:

$$Z(Y) = 0.5 * (1 + 0.049867347 * Y + 0.0211410061 * Y^2 + 0.0032776263 * Y^3 + 0.0000380036 * Y^4 + 0.0000488906 * Y^5 + 0.0000053830 * Y^6)^{-16}$$

For X < 0      P(X) = Z(-X)  
 for X > 0      P(X) = 1-Z(X)  
 for X = 0      P(X) = 0.5

52. The function in the calling program should be similar to P(X) where X is the standardized distance from the mean of a normal distribution. The approximate value of the function

$$P(X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^X e^{-t^2/2} dt$$

is returned to the calling program. No subroutines are called.

### ARRAY "F"

53. This array is used in several of the Monte Carlo overlay subroutines. Contained in array "F" are:

- all calculated factor of safety values,
- maximum and minimum factors of safety,
- class boundaries used in ideogram plot,
- frequency by per cent and count in each class interval.

54. Variables needed to define addresses of various values are:

- NSAMPL - number of samples,

- NBIN - number of class intervals.

55. Positions of various values are:

- calculated factor of safety values occupy addresses 1 - NSAMPL,
- minimum and maximum values occupy addresses NSAMPL + 1 and NSAMPL + 2 respectively,
- class boundaries used in ideogram plot occupy addresses NSAMPL + 3 through NSAMPL + NBIN + 3; this is space for NBIN + 1 class boundaries corresponding to the lower boundary on each class plus the upper boundary on the final class,
- frequency by count and per cent for each class interval; beginning with address NSAMPL + NBIN + 4, frequency by count and per cent alternate; frequency by per cent precedes frequency by count for each class beginning with the lowest class; this requires 2\*NBIN addresses.

56. Array "F" is stored at the end of blank common since this allows large sample sizes to be specified without fear of overflowing into another array.

57. The total number of values stored in array "F" is NSAMPL + 3\*NBIN + 3 where NSAMPL and NBIN are defined as above. When running a program using this array, enough field length should be specified before running to exceed the amount specified at compile time plus the above size. Subroutines using array "F" in the Monte Carlo package of subroutines are:

STATAN - "F(1)" corresponds with "WS(1)"  
 FRQTBL1 - "F(1)" corresponds with "F(1)"  
 STATO1 - "F(1)" corresponds with "SAMPL(1)"  
 INGPLT1 - "F(NSAMPL+3)" corresponds with "F(1)".

58. The working storage scheme for Array "F" is shown in Fig E-3.

### MONTOUT

59. This is an output routine to print Monte Carlo option input, and sampled and computed values at various stages of sampling, depending on the print code specified. It includes the entry point SAMPOUT at which the sampled input and corresponding output are actually printed. The CALL statement will depend on the deterministic

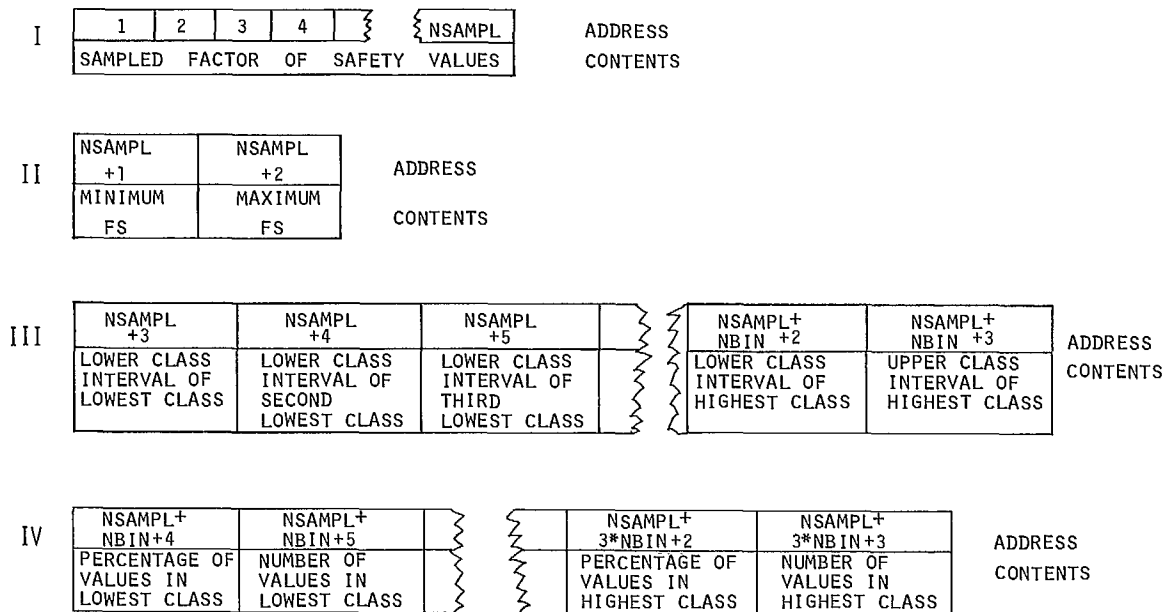


Fig E-3 - Layout of storage in array "F".

program with which the overlay is interfaced.  
(Note: it is used only by PLAFAM and TWOBAM).

#### Data Inputs

60. The input data required consists of the distribution of all input variables plus control information for the overlay, as described for the MONTE subroutine.

#### Program Options

61. Options, as outlined in the description of MONTE and STATAN, relate to the number and form of the distributions and the printout options.

#### Printed Output

62. The output is printed from subroutine STATAN, and the meaning of the output options is given in the description of STATAN. Typical output is given in Appendices A to D.

#### Other Outputs

63. There are none.

#### Flow Charts

64. Simplified flow charts for each subroutine are given as Fig E-4 to E-14. The overall flow chart for the Monte Carlo overlay is given in

Fig E-2.

#### Sample Runs

65. The output will depend somewhat on the program to which the overlay is attached. Typical outputs are shown in Appendices A to D.

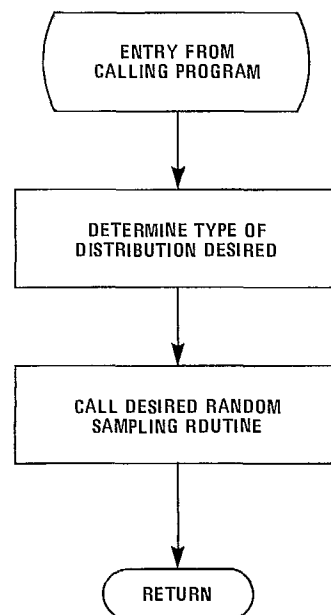


Fig E-4 - Flow chart for subroutine SAMPLE.

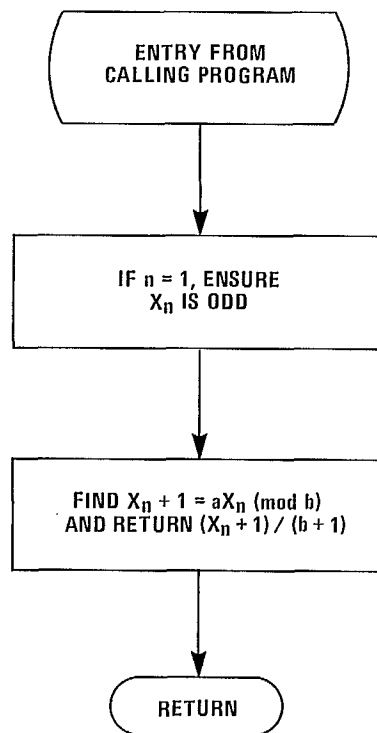


Fig E-5 - Flow chart for subroutine RANDOM.

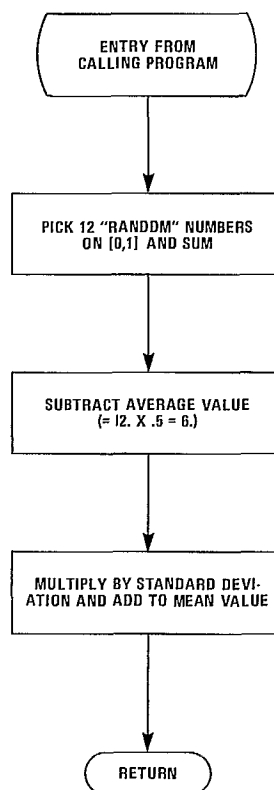


Fig E-6 - Flow chart for subroutine GAUSS.

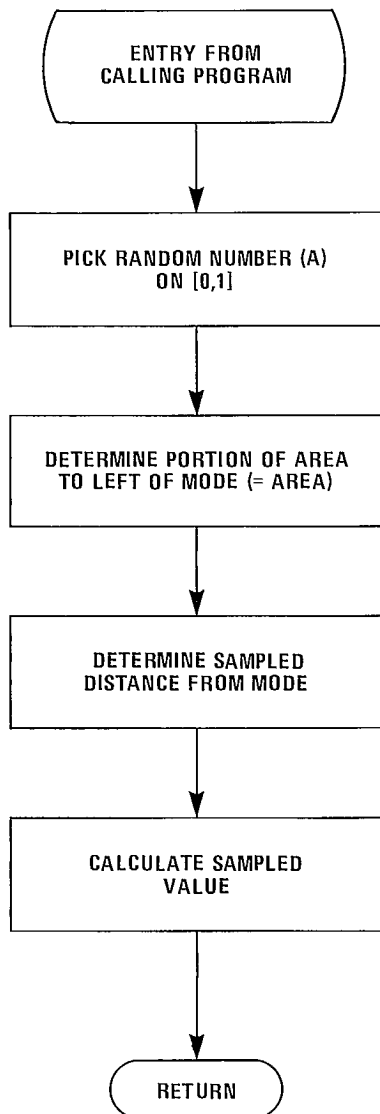


Fig E-7 - Flow chart for subroutine TRIDIS.

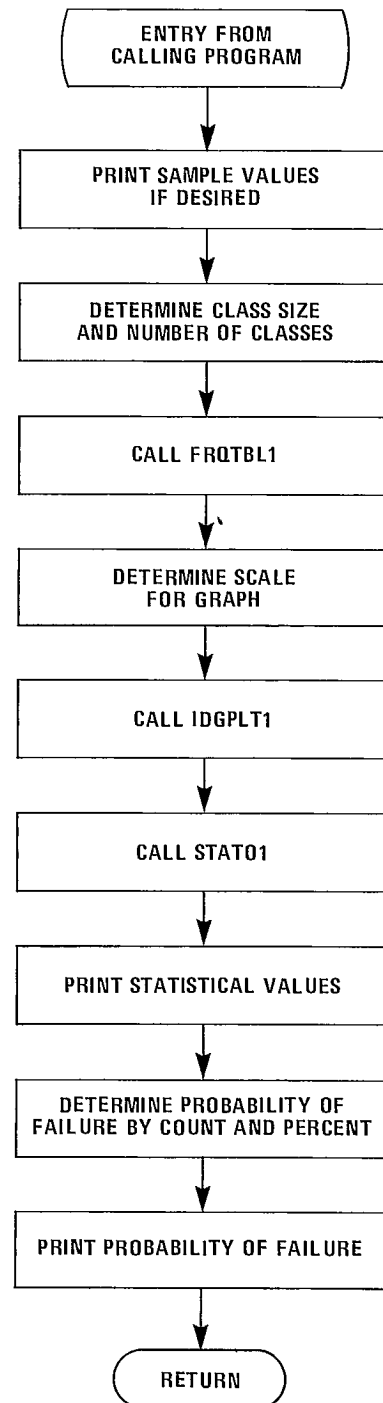


Fig E-8 - Flow chart for subroutine STATAN.

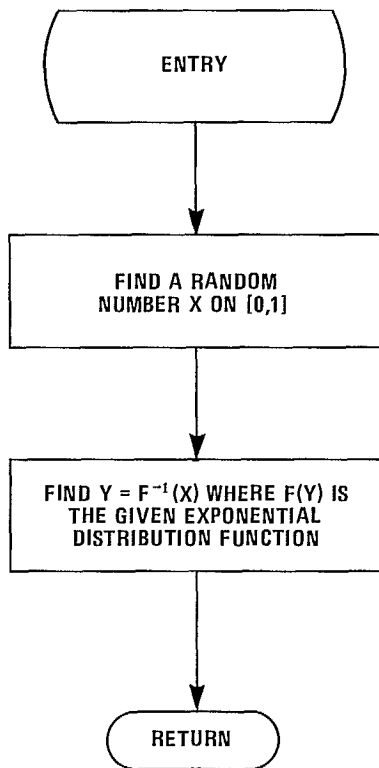


Fig E-9 - Flow chart for subroutine EXPEDIS.

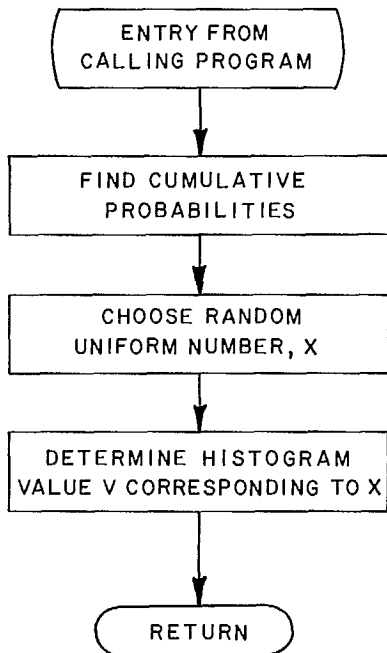


Fig E-10 - Flow chart for subroutine HIST0.

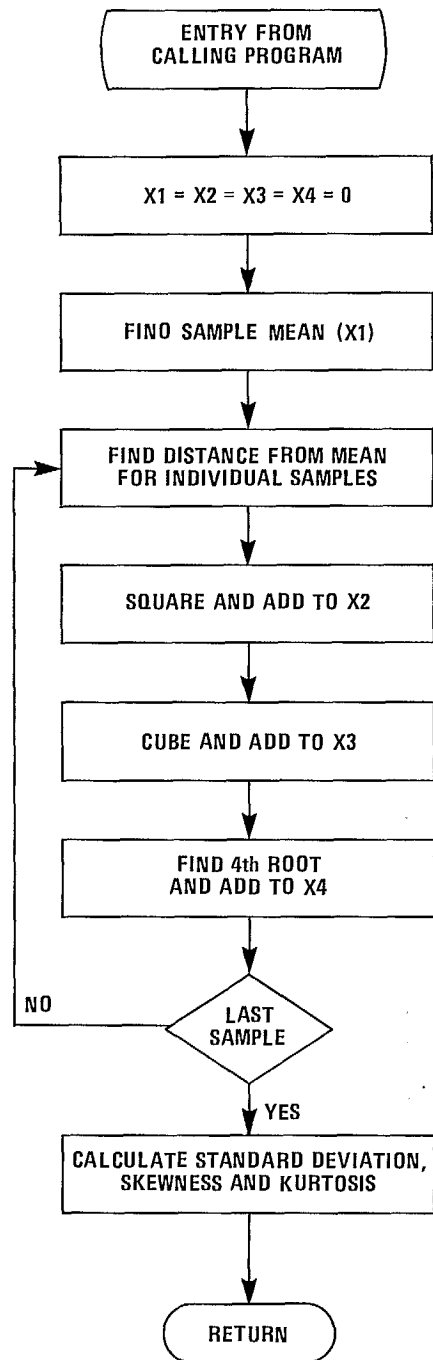


Fig E-11 - Flow chart for subroutine STAT01.



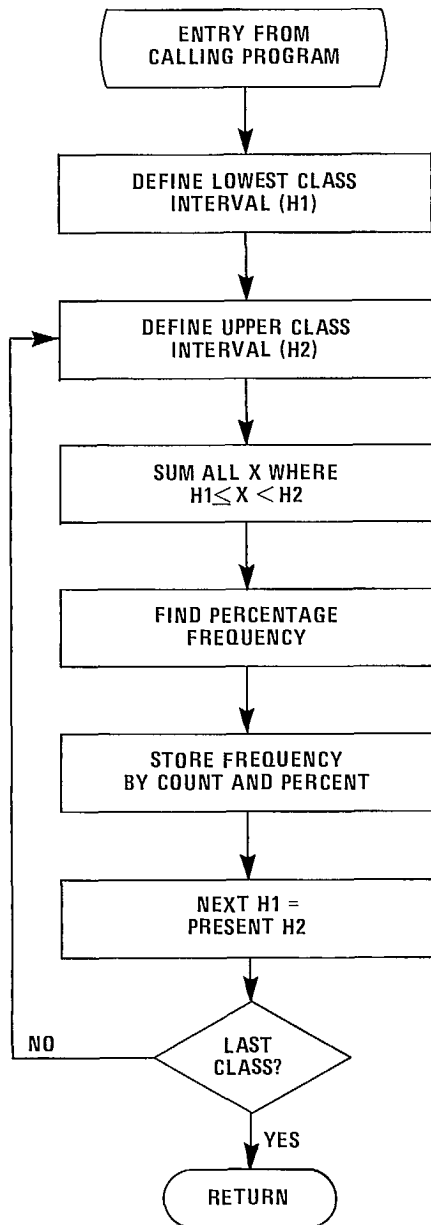


Fig E-12 - Flow chart for subroutine FRZTBL1.

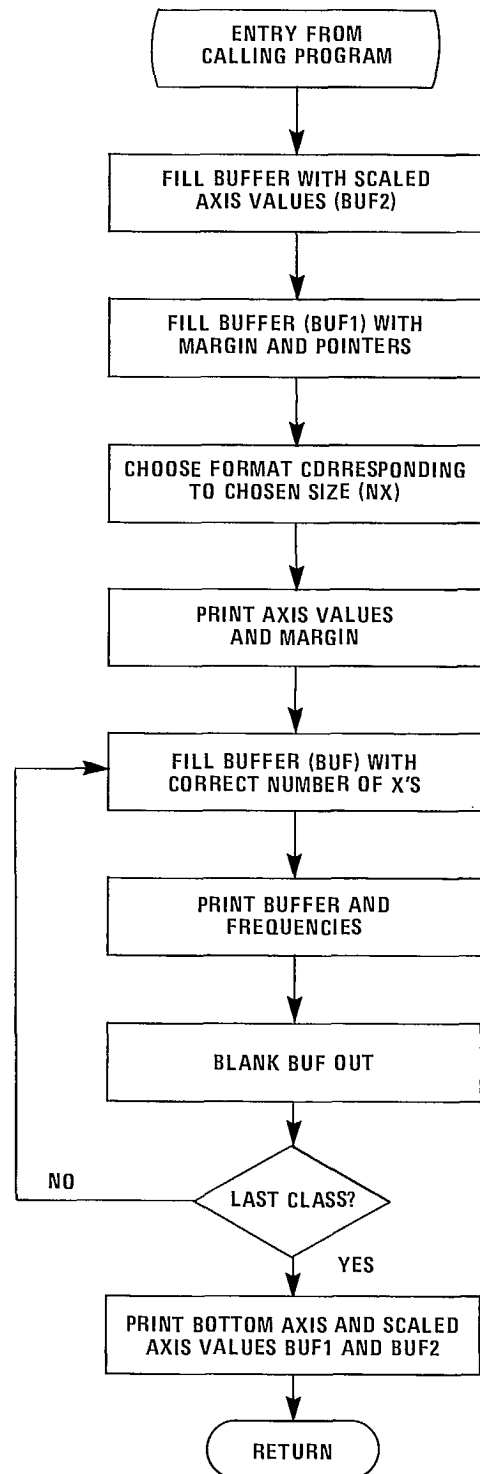


Fig E-13 - Flow chart for subroutine IDGPLT1.

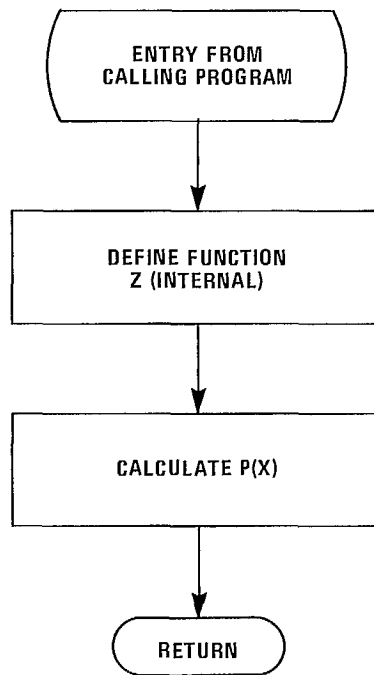


Fig E-14 - Flow chart for function P.

## SYSTEM DOCUMENTATION

### Computer Equipment

66. These subroutines were developed on a CDC 6600. The pseudo-random number generator exploits the word size of CDC equipment but can readily be replaced by any of the pseudo-random number generators available in other system libraries.

### Peripheral Equipment

67. Minimum peripheral equipment required are a card reader and a line printer.

### Variables and Subroutines

68. The main subroutines and variables have been described above. Library subroutines used are ABS, MOD, AMAX1, AMIN1, FLOAT, ALOG, AND, COS, EXP, SIN, SQRT, TAN, DATE, TIME, SECOND, ENCODE.

### Storage Requirements

69. The storage required is given by the formula

$$S = S1 + 943 + SVAR$$

where

S = total storage required,

S1 = fixed storage dependent on the

interfacing routines MONTE and MONTOUT,

SVAR = variable storage composed of  
NSAMPL (the number of samples)  
+ 3\*NBIN (the number of class  
intervals in the ideogram plot)  
+ 3.

70. The storage is therefore dependent on the deterministic program with which the overlay is interfaced. The fixed storage S1 is given below in units of decimal words for the four slope stability programs:

PLAFAM	1488
TWOBAM	1561
WINTAM	2211
GENSAM	13226

Note that a dynamic storage allocation is used in part. This means that a sufficiently large array WS at compilation time or sufficient core at execution time must be provided so that there is SVAR storage available during program execution.

### Maintenance and Updates

71. Updated December 1976 (HISTO added)

## OPERATING DOCUMENTATION

### Operating Instructions

72. There are no special operating instructions.

### Operating Messages

73. There are no special operating messages.

### Control Cards

74. No special control cards are required.

### Error Recovery

75. Not applicable.

### Run Time

76. Execution time of a program incorporating the Monte Carlo overlay is dependent on the types of distributions used for the statistical variables and the number of samples. The run time can be estimated from the formula.

$$T = \text{NSAMPL} * (U1 + U2)$$

where

T = run time of the program with the probabilistic analysis,  
 U1 = unit time required to sample the statistical variables,  
 U2 = unit time required to run the deterministic part of the program.

77. U1 can be determined by summing the times required for sampling each variable. These times are approximately as follows:

DISTRIBUTION TYPE	SAMPLING TIME (CPS)
normal	0.88 msec
triangular	0.16 msec
uniform	0.09 msec
truncated normal	2.5 msec*
exponential	0.15 msec (with no upper limit)
histogram	0.75 msec

\* depends on truncation limits

78. The unit sampling time with truncated normal distribution is obtained by taking the lower and upper limit to be two and six standard deviations away from the mean.

79. U2 for the deterministic programs used so far is approximately the following when the most detailed printout option is used:

PROGRAM	RUN TIME (CPS)
PLAFAM	0.02 sec ( $\approx$ 2.4 sec for step path simulation)
TWOBAM	0.07 sec
WINTAM	0.03 sec
GENSAM	3.0 sec

## GLOSSARY



(Dimensional symbols in brackets eg [D] indicate the physical nature of the term, ie L stands for any unit of length. M for mass, F for force, T for time, and D is used if the term is dimensionless. Descriptive terms, eg bench, have no symbol)

#### ANGLE OF INTERNAL FRICTION $\phi$ [D]

The maximum angle of obliquity between the normal and the resultant stress acting on a surface within a soil or rock.

#### COHESION $c$ [FL<sup>-2</sup>]

The portion of the shear strength,  $S$ , indicated by the term  $c$ , in Coulomb's Equation,  $S = c + \phi \tan \phi$ , where  $\phi$  is the angle of internal friction. It has the nature of an intergranular binding force. Sometimes referred to as apparent cohesion when it is known that the straight-line relationship is not valid but is assumed for a limited range of normal stress.

#### CRITICAL CIRCLE (CRITICAL SURFACE)

The sliding surface for which the factor of safety is a minimum in an analysis of a slope in ductile ground where average stresses can be used.

#### CRITICAL DIP $\beta_c$ [D]

The minimum dip of a discontinuity striking parallel to a slope face on which sliding can occur taking into account the frictional resistance of the discontinuity, seepage and earthquake forces.

#### CRITICAL SLOPE ANGLE $i_c$ [D]

The maximum angle with the horizontal at which a slope of a given height will stand unsupported.

#### CUMULATIVE DISTRIBUTION FUNCTION CDF

A function, or curve, expressing the probability of a parameter, or random variable, having a value equal to or less than a specified value, or argument of the function.

#### DENSITY (MASS DENSITY) [ML<sup>-3</sup>]

Mass per unit volume.

#### DETERMINISTIC

Describes a parameter whose value is known with certainty.

#### DIP [D]

The angle of a slope, vein, rock stratum, or borehole as measured from the horizontal plane downward. Where applicable, the dip is measured normal to the strike.

#### DISPERSION

The variability of observed data of a simple property.

#### DOMAIN

The areal extent of a given environment (15).

#### DRAWDOWN [L]

The vertical distance the free water elevation is lowered or the reduction of the pressure head due to the removal of free water.

#### DUCTILE

Pertaining to a substance that readily deforms plastically (15), arising from metal that is capable of being drawn through the opening of a die without breaking and with a reduction of the cross-sectional area.

#### EQUIPOTENTIAL LINE

Line along which water will rise to the same elevation in piezometric tubes (14).

#### EXPONENTIAL DISTRIBUTION

A probability density function characterized by an exponential curve defined by one constant, which is equal to the mean value when the range is from zero to infinity. The cumulative distribution function is also an exponential curve.

#### FABRIC

The orientation in space of the elements of a rock mass (15).

**FACE**

The vertical, or near-vertical, surface of rock exposed by mining operations.

**FACTOR OF SAFETY [D]**

The ratio of the forces tending to prevent sliding to those tending to cause sliding.

**FLOW LINE**

The path that a particle follows under laminar flow conditions (14).

**GROUND WATER LEVEL**

The level below which the pores and fissures of the rock and subsoil, down to unknown depths, are full of water (15). Or elevation at which the pressure in the water is zero with respect to the atmospheric pressure (14), see Line of Seepage.

**HISTOGRAM**

Measured values of a parameter are grouped into classes and the number of occurrences, or frequency, plotted as a vertical bar over the range, or class, of the parameter's value. The relative area under the bar represents the probability of occurrence of that dip for that population.

**HYDRAULIC GRADIENT  $i$  [D]**

The loss per unit distance of elevation plus pressure head. Critical Hydraulic Gradient: Hydraulic gradient at which the intergranular pressure in a mass of cohesionless soil is reduced to zero by the upward flow of water (15).

**IDEOGRAM**

A vertical bar graph showing the frequency of occurrence of various safety factors in a Monte Carlo analysis.

**JOINT**

In geology, a plane or gently curved crack or fissure, which is one of an approximately parallel set of fissures ranging from a few inches to many feet apart. Joints occur in rocks of nearly all kinds and generally in two or more

sets that divide the rocks into polyhedral blocks.

**JOINT SYSTEM**

Consists of two or more joint sets or any group of joints with a characteristic pattern, such as a radiating pattern, a concentric pattern, etc. (15).

**KURTOSIS [D]**

A measure of the peakness, or flatness, of a probability density function. A normal distribution has a kurtosis of 3.0.

**LAYER**

A bed or stratum of rock separated from the adjacent rock by a plane of weakness (15).

**LENGTH [L]**

Usually a long dimension parallel to the ore-body, unlike width and thickness.

**LINE OF SEEPAGE (SEEPAGE LINE) (PHREATIC LINE)**

The upper free water surface of the zone of seepage (14).

**MOHR ENVELOPE (RUPTURE ENVELOPE)  
(RUPTURE LINE)**

The envelope of a series of Mohr Circles representing stress conditions at failure for a given material. According to Mohr's Strength Theory, a failure envelope is the locus of points the coordinates of which represent the combinations of normal and shearing stresses that will cause a given material to fail (14).

**MONTE CARLO**

Referring to the process of random sampling from a defined distribution of values of a parameter. It simulates the occurrence of various values of strength and geometric properties in nature.

**NORMAL DISTRIBUTION, STANDARD NORMAL,  
NORMAL CURVE, GAUSSIAN**

The distribution of numerical data,  $x$ , about an average value,  $m$ , that follows the gaussian



equation:

$$y = \frac{1}{s\sqrt{2\pi}} \exp \left[ \frac{-(x-m)^2}{2s^2} \right]$$

where  $y$  is the frequency of occurrence and  $s$  is the standard deviation of the data.

#### PARAMETER

A quantity constant in a special case but variable in different cases, eg angle of internal friction, modulus of deformation, etc.

#### PIEZOMETER

A device for measuring the hydrostatic pressure at a point in the ground. Simple piezometers are open groundwater wells.

#### PROBABILITY

It is concerned with unpredictable individual events but which are predictable in large numbers. It is the frequency ratio of occurrence of one event that can be expected in an infinitely large population of events. For less than an infinite population, it has the meaning of relative likelihood of occurrence, and as such it can be a personal opinion instead of being based on observations or analysis, eg 'I believe there is a 1 in 3 likelihood of hitting ore at this location'.

#### PROBABILITY DENSITY FUNCTION

It is the relation between the relative likelihood of occurrence of a parameter or event and the numerical value of the event.

#### PROBABILITY OF INSTABILITY

The probability that the variations in length and spacing of discontinuities will combine with those governing the probability of sliding to permit instability.

#### PROBABILITY OF SLIDING

The probability that, given the critical geometry, the variations in strength, groundwater and dip will combine to produce sliding.

#### PROGRESSIVE FAILURE

Failure in which the ultimate resistance is progressively, rather than simultaneously, mobilized along the ultimate failure surface.

#### RELIABILITY

The obverse of the probability of instability,  $P$ , ie  $1-P$ , or the probability that strength exceeds stress.

#### ROCK MASS

The in situ rock made up of the rock substance plus the structural discontinuities.

#### ROCK SUBSTANCE

The solid part of the rock mass, typically obtained as drill core.

#### ROCKFALL

The relatively free fall of a detached rock of any size from a steep slope.

#### RANDOM SAMPLE

A sample taken in such a way that there is an equal chance of every member of the target population being selected or observed. By contrast, a biased sample is one that is taken in a manner that results in a greater possibility of it being selected or observed than others in the target population, eg a set of dip angles obtained from core will be biased against dips parallel to the hole.

#### SAFETY FACTOR $FS [D]$

The ratio of the ultimate stress to the working stress at fracture or yield.

#### SAMPLE POPULATION

The group of data from which actual samples are taken, which may or may not be equivalent to the target population, eg the dip of the joints available for measurement on the faces of the benches may not include all representative joints.

**SHEAR FAILURE**

Failure resulting from shear stresses.

**SHEAR STRENGTH  $[FL^{-2}]$** 

The internal resistance offered to shear stress. It is measured by the maximum shear stress, based on original area of cross-section, that can be sustained without failure (14).

**SKEWNESS  $[D]$** 

A measure of departure from symmetry of a probability density function. A normal distribution has a skewness of zero.

**STANDARD DEVIATION  $S$** 

The square root of the quotient of the sum of the squares of the difference between the arithmetic mean,  $m$ , and a number of values of a quantity,  $x$ , divided by the number,  $n$ . It is a measure of the dispersion of the number of values about the mean, ie,

$$S = \pm \sqrt{(m-x)^2/n}$$

**STOCHASTIC**

Describing a parameter whose exact value either is unknown and can only be measured imprecisely or is subject to variations in nature.

**STRIKE  $[D]$** 

The bearing of a horizontal line in the plane of an outcrop, joint, fault, or the structural plane.

**STRUCTURAL FEATURE**

In geology, a feature representing a discontinuity of mechanical properties, such as a joint, fault, or bedding plane.

**TARGET POPULATION**

The entire group of data from which representative samples are to be taken, eg the dip of the joints in a set.

**THICKNESS  $[L]$** 

A dimension, together with width, usually

referring to the dimension of an orebody normal to its plane.

**TOE**

The bottom of a slope.

**TRIANGULAR DISTRIBUTION**

The probability density function characterized by a finite range and linear variations from zero to a maximum.

**TRUNCATED NORMAL DISTRIBUTION**

A normal distribution with one or both tails terminated abruptly, which is appropriate for parameters that cannot have values beyond this point, eg cohesion less than zero.

**UNIFORM DISTRIBUTION**

A rectangular probability density function.

**UNIT WEIGHT  $[FL^{-3}]$** 

Weight per unit volume. Dry Unit Weight (Unit Dry Weight),  $\gamma_d [FL^{-3}]$ : The unit weight that, when multiplied by the height of the overlying column of ground, yields the effective pressure due to the weight of the overburden (1). Saturated Unit Weight,  $\gamma_{sat} [FL^{-3}]$ : The wet unit weight of a granular mass when saturated (1). Submerged Unit Weight (Buoyant Unit Weight,  $\gamma_b [FL^{-3}]$ : The weight of the solids in air minus the weight of water displaced by the solids per unit of volume of mass; the saturated unit weight minus the unit weight of water. Wet Unit Weight (Mass Unit Weight),  $\gamma_m, \gamma_t [FL^{-3}]$ : The weight (solids plus water) per unit of total volume of mass, irrespective of the degree of saturation (14).

**VARIANCE**

A measure of the dispersion of a random variable, which is equal to the square of the standard deviation.

**WIDTH  $[L]$** 

A dimension, together with thickness, usually referring to the dimension of an orebody normal to its plane.

## ABBREVIATIONS AND SYMBOLS

c	- cohesion	FS	- safety factor
D	- height of groundwater above the toe of the slope	S	- safety factor; shear strength; standard deviation
eq	- equation	3-d	- three-dimensional
H	- height	t	- metric tons
i	- dip of slope face	T	- short tons; tangential force
$i_c$	- critical slope angle	q	- surcharge load on the crest of a slope
in.	- inch	u	- pore pressure
k	- kilo	V	- volume
kg	- kilogram	$\beta$	- dip of a sliding plane in plane shear
m	- metre	$\gamma$	- density
M	- mean		- angle between a rock face and a joint plane
N	- Newton; normal force	$\delta$	- friction angle
psf	- pounds per square foot	$\phi$	- normal stress
psi	- pounds per square inch	$\sigma$	- unit weight
P	- probability	$\gamma$	- shear stress
RN	- random number	$\tau$	