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USE OF COMPUTERS FOR SLOPE STABILITY ANALYSIS

D.G. Fredlund
Professor

University of Saskatchewan, Saskatoon, Canada

SYNOPSIS During the past few decades the costs related to computer hardware have decreased while the costs associated with computer software have increased significantly. As a result, the software has become of greater importance. Most software development has placed emphasis on the engineering algorithms involved and overlooked the importance of features such as data input, data verification and output interpretation. This paper reviews the history of slope stability software development and briefly assesses the various software packages that are available. A desirable specification for slope stability computer programs is presented.

INTRODUCTION

The factor of safety of either a natural or man-made slope is generally analyzed using a limit equilibrium method of slices. The consideration of all forces associated with each slice reveals that the problem is indeterminate in terms of the equations of equilibrium and the failure criterion. The most common procedures to render the analysis determinate have involved making an assumption regarding the interslice forces (Fredlund and Krahn, 1977). Varying assumptions regarding the interslice forces have led to approximately half a dozen commonly used methods of slices. Each of these assumptions has led to a non-linear factor of safety equation, which must be solved using an iterative, numerical procedure. Thus, for each assumed failure surface, some of the forces associated with each slice must be recalculated for each iteration until convergence has been achieved. One exception is the Ordinary or Fellenius method, which simply ignores the interslice forces. This method can lead to substantial error and is no longer commonly used in practice (Whitman and Bailey, 1967).

The location of the failure plane is generally unknown for stability problems associated with design. Some combination of the most highly stressed surface and the lowest shear strength will lead to the minimum factor of safety. The shape of the failure surface may be either circular, non-linear, or some combination of a circular and linear portion (i.e., composite) (Figure 1). It is easy to visualize a study for the minimum factor of safety involving in excess of 1000 trial failure surfaces. Bishop (1955) estimated a time of one hour to compute the factor of safety for one trial failure surface using the simplified Bishop method. Other methods can require considerably more time and are not conducive to long-hand calculation.

The description of the computations required to solve for the minimum factor of safety suggests that consideration should be given to the use of a high speed digital computer in order to perform the calculations accurately within a reasonable time scale. Further consideration reveals that the input data required to describe the problem is rather minimal. The coordinates of the surface of the slope along with the boundaries of all soil layers must be determined. Suitable shear strength parameters must be evaluated for each soil type. Also, the present and (or) future pore-water pressures within the slope must be measured or predicted. The above information remains constant for a large number of possible analyses. Slight modifications of the geometry, soil properties or pore-water pressure conditions can readily be re-analyzed using the computer.

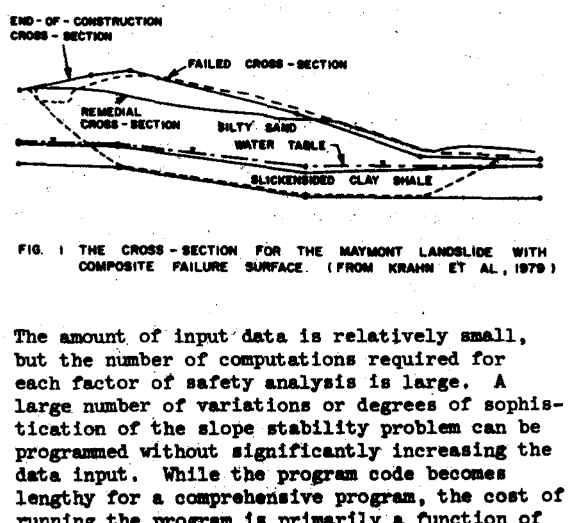

FIG. 1 THE CROSS - SECTION FOR THE MAYMONT LANDSLIDE WITH COMPOSITE FAILURE SURFACE. (FROM KRAHN ET AL., 1979)

The amount of input data is relatively small, but the number of computations required for each factor of safety analysis is large. A large number of variations or degrees of sophistication of the slope stability problem can be programmed without significantly increasing the data input. While the program code becomes lengthy for a comprehensive program, the cost of running the program is primarily a function of the method of analysis being used and the number of slices into which the geometry is divided (Fredlund, 1978).

The digital computer must be regarded as only one of the tools required in analyzing slopes, keeping in mind, however, that it is a very important tool. The following steps are suggested (Fredlund, 1978) with respect to the use of slope stability computer software: "(1) Obtain an approximate solution for the problem, either from stability charts or from hand calculations on a simplified form of the problem. (2) Perform the computer analysis of the actual problem. (3) Compare the 'approximate' and 'computer results and resolve anomolies. (4) Modify appropriate variables (i.e., geometry, soil properties or water conditions) and check the sensitivity of the factor of safety to these variables. (5) Make the necessary engineering decisions and plot the significant results."

This paper attempts to summarize the features of computers and computer software available for slope stability analysis. The types of computing facilities available are dealt with briefly. The history of slope stability software development is reviewed and the various types of software packages are briefly assessed. A desirable specification for slope stability computer programs is presented. The main problems related to the use of slope stability software are summarized along with recommendations regarding furture usage.

COMPUTER DEVELOPMENT

The use of computers in civil engineering commenced in the 1950's with universities receiving large, mainframe computers. It started at the graduate student level and found its way into the undergraduate curriculum in the 1960's. The latter part of the 1960's witnessed the development of interactive computing systems. In the 1970's the development of microprocessors brought the computer to a compact, inexpensive device suitable for office and home use. Presently, the two most extensive applications of computers are for management information systems and scientific systems.

Presently, there are five classes of computers which can be categorized in terms of their capabilities and cost (Schiffman, 1977). Ranging from the smallest to the largest, these are: hand-held programmable calculators, microprocessors, minicomputers, midi-computers and large, mainframe computers. The large, mainframe computers have in the order of one to eight million bytes (characters) of memory, whereas the microprocessors have a few thousand bytes of memory. There is a considerable variation in the memory storage of the mini- and midi-computers.

Engineering problems such as slope stability analysis generally require a computer with a large memory and the capacity to handle a large number of executable statements. Large, mainframe computing systems have been outside of the budget of all but a few large engineering firms. since they have the capacity to handle many civil engineering problems. However, several few problems have arisen. First, the engineering firms generally handle their accounting and management on the same facility. These take priority over engineering applications such as slope stability, which require "blocks of time" in an unscheduled or erratic bases. Second, there is a lack of suitable engineering software or intermediate computer systems. The lack of software security does not encourage investment in software development.

One solution to the above problems has been the establishment of networks of large, mainframe computers. Generally, access to the network is provided through terminals on a priority basis. This type of facility gives engineering firms access to large, mainframe computers capable of supporting significant scientific programs (Robert and Wessler, 1970). The development of the computer networkds should become increasingly significant with the establishment of fast, reliable, low cost communication systems with essentially immediate access to the computer through office terminals. The communication of data can be accomplished using a variety of devices ranging from ordinary telephone circuit to satellites for intercontinental transmission.

The most commonly preferred type of terminal involves a keyboard, a cathode ray tube, and a printing device capable of producing hardcopy output. This system holds good promise for slope stability analysis since there is a relatively small amount of input data required on one hand and an extensive amount of computations required on the other hand. This procedure of providing large, engineering computer packages is becoming increasingly more economical with the relative decrease in the cost of computer hardware.

HISTORY OF SLOPE STABILITY SOFTWARE

There has always been a lag of several years between the computer technology available and that used by the civil engineering profession. From a pshychological standpoint there has been a suspicion towards the use of the computer as a "black box" with no judgments based on experience being input by the engineer. Although the computer has now been essentially accepted for engineering computations, its use is not near as extensive as might be expected (Fredlund, 1978)

The use of computers for performing slope stability analysis commenced in the 1950's (Little and Price, 1958; Horn, 1969). In 1967, Whitman and Baiely estimated that from 25 to 50 slope stability computer programs had been written in the United States. Most of these were not comprehensive and often used approximate computational procedures. In subsequent years many additional slope stability computer programs of varying degrees of complexity have been written. Most of these programs have had limited distribution and have not been maintained by the distributor. As a result, the usage of each program is generally minimal. At present there is a limited number of slope stability computer programs available that can be considered properly documented, portable and fully debugged. In general, the development of suitable slope stability software has lagged seriously behind the capabilities afforded by computer hardware.

A survey of Canadian users in 1977 showed that for slope stability problems, the computer is used primarily by universities and large engineering groups. The key findings of the survey of the universities was as follows: (Fredlund, 1978).

1. Most universities in Canada have one or more slope stability computer programs available for their use.
2. Most computer programs have been developed by a graduate student or a staff member to solve for the factor of safety by one of the methods of slices. The programs serve an immediate need and are not comprehensive nor suitable for distribution. The programs are generally in an *ad hoc* state with poor documentation.
3. The programs are generally used by one university staff member for some teaching and a limited amount of consulting. However, most universities still do not make significant use of a slope stability computer package as a teaching tool in geotechnical engineering.
4. Universities appear to be slow, in general, to seek out and use programs not written at their institution.
5. At many universities there seems to be little emphasis on the application of slope stability computer programs.

The key findings of the survey of engineering firms are as follows:

1. Upkeep of the programs and familiarity with their usage are problems that arise mainly as a result of the extensive time intervals between successive runs of the program.
2. Small engineering consulting firms generally do not maintain their own slope stability software. Sometimes assistance is obtained from larger consulting firms or utilization is made of computer programs available through software service bureaus. Most often an attempt is made to manage without using computer programs.
3. Consulting engineering firms desire to see more education at universities on the application of slope stability programs.

The main concerns from the survey were the lack of well documented, fully maintained, slope stability computer packages that were accompanied by a comprehensive, standard set of published example problems. The computer software that appears to best satisfy the requirements of engineering practice are those that have been maintained on a commercial basis over a period of several years.

SLOPE STABILITY SOFTWARE SPECIFICATION (ALGORITHM)

There are many factors that require consideration in a comprehensive slope stability computer program. A common complaint is that the scope of the program is too narrow and the program will not handle the wide range of problems encountered in practice. An attempt is made herein to produce a desirable specification for slope stability software. The design of an earthfill dam (Figure 2) is used as an example to demonstrate the software features.

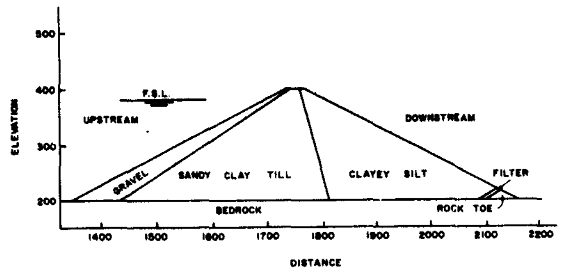

FIG. 2 EXAMPLE PROBLEM TO DEMONSTRATE THE FEATURES REQUIRED IN A SLOPE STABILITY COMPUTER PROGRAM

1. Type of Analysis-
The limit equilibrium methods of slices most commonly required are: (i) The Ordinary method. Other names given to this method are the Fellenius, Swedish Circle, Conventional and Normal method. (ii) The simplified Bishop method. (iii) Force equilibrium methods such as Taylor's modified Swedish method, the Corps of Engineers' method, and the Lowe and Karafiath method. (iv) The Janbu simplified and generalized methods. (v) The Morgenstern-Price method. These methods differ basically in the physics used in deriving the factor of safety equation and the assumption used to render the problem determinate (Fredlund and Krahn, 1977).

Most computer programs solve for the factor of safety using only one method. In some cases, the Ordinary method is solved first in order to obtain an estimated factor of safety for another method. However, the Ordinary method no longer serves a significant role in design or analysis due to theoretical limitations of the method.

Engineering consulting firms are sometimes requested by various agencies to calculate the factor of safety using a specified method. It becomes difficult to maintain independent computer software for each method of slices. However, there is little additional programming required to have more than one method of analysis in a computer program since all methods utilize essentially the same basic variables. Comparative type studies are also made easier when the basic variables in the analysis are computed in the same manner.

2. Shape of the Failure Surface-
It is highly preferrable to be able to accommodate both circular and non-circular modes of failure within one computer program since both modes are often possible on a project. This would be the case in the example problem (Figure 3), particularly if the bedrock were shale and the upper portion were somewhat softened. Whenever several different soil types and strength conditions are encountered, the possibility of a non-circular failure surface should be investigated. Most slope stability computer programs accommodate either circular or non-circular failure surfaces but few programs handle both options.

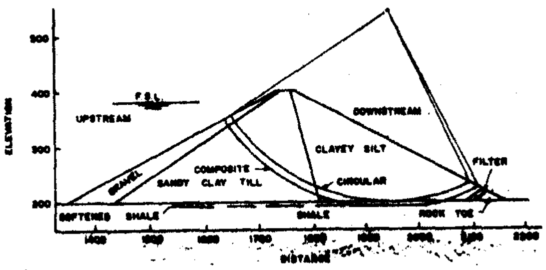

FIG. 3 TYPICAL CIRCULAR AND COMPOSITE ASSUMED FAILURE SURFACES

Fredlund and Krahn (1977) extended the simplified Bishop method and Spencer method to accommodate non-cricular failure surfaces. It was also shown that the factors of safety obtained for moderately non-circular failure surfaces were similar to those obtained using the Morgenstern-Price method.

3. Number of Soil Layers-
A slope stability computer program should be capable of accommodating at least ten soil layers. Generally it is not possible to reasonably define the soil parameters for large numbers of soil strata. When large numbers of soil types occur it is usually possible to combine soil layers either due to similarity of soil properties or the obvious insignificance of some strata. For example, the filter material and the rock toe (Figure 2) may not need to be considered as independent soil types.

The program should be able to handle soil layers that are discontinuous. This commonly occurs where a strata pinches out or in zones of limited extent in an earth fill dam (Figure 2).

4. Partial Submergence-
Partial submergence is of interest when analyzing long-term stability and rapid-drawdown of an earthfill dam. In addition, many other cases of natural and man-made conditions involve partial submergence. Complete submergence should also be accommodated as in the case of subterranean landslide studies. The submerging liquid should not be limited to pure water.

Tension cracks can also be considered as a form of partial submergence. Since the water is in a crack in the soil, special consideration must be given to programming this situation.

5. Surcharging and Berming-
The effect of surcharging and berming should be able to be accommodated.

6. External Line Loads-
The program should handle externally applied line loads in order to handle situations involving the effects of a dragline, a retaining wall, an anchor, etc.

7. Earthquake Loadings-
The increased concern over earthquake resistance of dams makes the "pseudo-static" type of analysis a highly desirable feature in slope stability software. The "pseudo-static" type of analysis assumes that a horizontal force is applied in the direction of the slope through each slice. The magnitude of this force is expressed as a function of the weight of the slice. This procedure does not accurately define the behavior of a slope under dynamic loading conditions, but in the interim it is often used for lack of verified, superior procedures (Chowdhury, 1978).

8. Pore-Water Pressures-
Users of slope stability computer programs often have difficulty in simulating the pore-water pressure conditions. Pore-water pressures can be subdivided into pressures that are dependent upon the total stress conditions and those that are independent. Possible situations of interest can best be visualized by considering the significant design stages of an earthfill dam. These are: (i) The end-of-construction stage. (ii) The long-term stability. (iii) The rapid-drawdown case. A slope stability computer program should be capable of handling each of these cases.

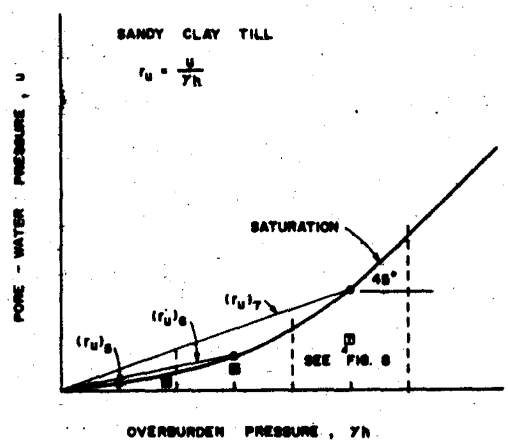

FIG. 4 NONLINEARITY OF RELATIONSHIP BETWEEN PORE - WATER PRESSURE AND OVERBURDEN PRESSURE

The pore-water pressures at the end-of-construction of a compacted fill are a function of the applied total stresses. One of several procedures can be used to input these pore-water pressures. The simplest procedure is to use the pore pressure coefficient, r_u, to specify a linear relationship between pore-water pressure and the overburden pressure. The main problem with this procedure is that the actual relationship is non-linear (Hilf, 1948; Bishop, 1957) as shown in Figure 4. This difficulty is most conveniently overcome by programming to accept a non-linear pore pressure versus total stress relationship. An alternate solution involves subdividing the soil types (i.e., sandy clay till and clayey silt) into more zones (Figure 5) in accordance with depth and using a different pore pressure

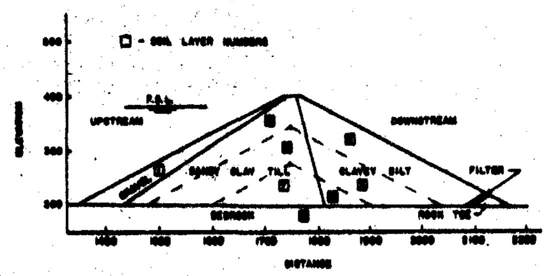

FIG. 5 SUBDIVISION OF THE COMPACTED FILL TO ACCOUNT FOR NONLINEARITY OF THE PORE PRESSURE COEFFICIENT

coefficient, r_u, for each depth (Figure 4). In the example shown the number of soil layers has increased from 4 to 8 due to subdivision. It is also possible to use a finite element stress analysis along with A and B pore pressure parameters to describe the pore-water pressure over a grid of locations superimposed upon the geometry cross-section (Figure 6). The computer would then use an interpolation technique to obtain the pore-water pressure at the base of each slice.

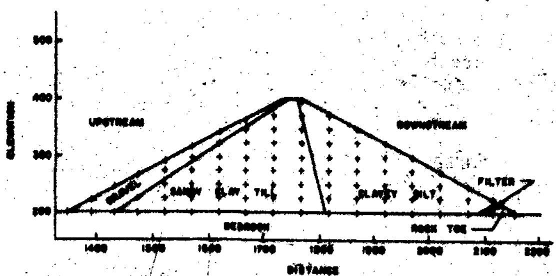

FIG. 6 GRID OF PORE-WATER HEADS SUPERIMPOSED ON GEOMETRY

The pore-water pressures for the long-term stability analysis of the earthfill dam are obtained from a steady state flownet. Figure 7 shows the flownet for the example problem along with an assumed slip surface and the corresponding piezometric line. Generally the uppermost flowline is used as a piezometric line for each soil. This produces a slightly conservative analysis since the actual piezometric line for each assumed slip surface is below the uppermost flowline. The error in this procedure is generally minor but increases as the gradient on the uppermost flowline increases. It is also possible to use the flownet to define the pore-water heads on a grid of points superimposed on the cross-section. The pore-water pressures are generally more precise using this method, but the additional cost may not be warranted in most cases.

The pore-water pressures for the rapid-drawdown case can be estimated from a flownet. Figure 8 shows the flownet for the 75 percent drawdown case along with an assumed slip surface. Although the flownet appears to have changed significantly from the steady state seepage case (Figure 7), the pore-water pressures along the assumed slip surface can, in general, be ade-

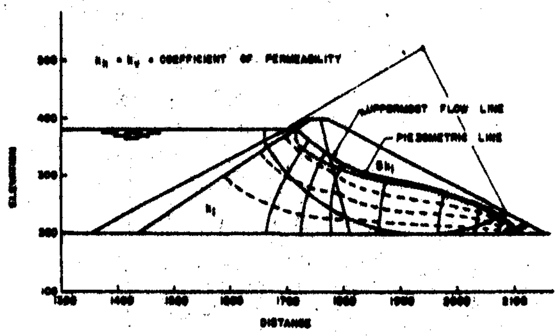

FIG. 7 FLOWNET FOR STEADY STATE SEEPAGE SHOWING PIEZOMETRIC LINE FOR ASSUMED FAILURE SURFACE

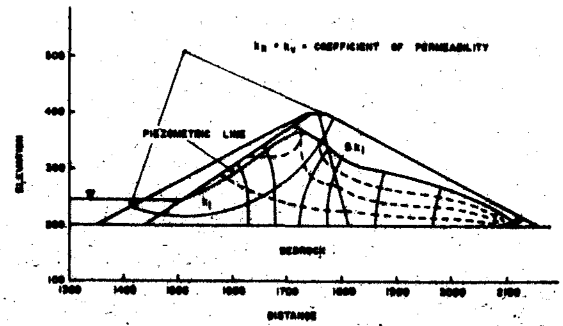

FIG. 8 FLOWNET CORRESPONDING TO 75 PERCENT DRAWDOWN

quately defined using the uppermost flowline and the upstream surface of the sand clay till as a piezometric line for the assumed failure surface. A grid of pore-water heads could again be superimposed on the geometry for the rapid-drawdown case.

The pore-water pressures for most other slope stability problems encountered in engineering practice can be adequately handled if the various design stages of an earthfill dam can be simulated. When total shear strength parameters are used for a soil layer, it is not necessary to specify any pore-water pressure conditions. A slope stability computer program should allow the inter-mixing of total and effective strength parameters for different soil layers.

7. Grid Search-

Numerous search routines have been devised to locate the center of rotation corresponding to a minimum factor of safety. These generally result in savings in computing costs; however, uncertainties exist in these procedures when considering problems with complex geometries or composite failure surfaces. For this reason many practicing geotechnical engineers are reluctant to use a search technique which does not completely specify the region searched. The more reliable procedure is to define the 'x' and 'y' coordinates of a grid of centers of rotation and to specify several radii ranging between two 'y' coordinates. At each grid center the radius corresponding to the minimum factor of safety should generally be enveloped above and below

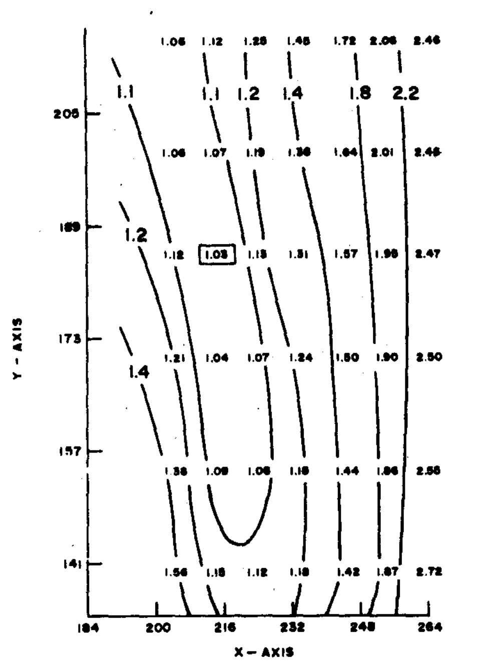

FIG. 9 DIGITAL PLOT OF THE MINIMUM FACTORS OF SAFETY

by radii with higher factors of safety. The minimum factors of safety should be plotted to ensure that the overall minimum factor of safety does not lie on the edge of the selected grid (Figure 9).

8. Units-
It is important to be able to describe the geometry, soil properties and pore-water pressures in any consistent set of units. The main conversion required is the unit weight of water for changing the pore-water head to a pore-water pressure.

The above requirements are specified to assist the user when attempting to select or develop a slope stability computer program. These requirements are by no means exhaustive, but will give the geotechnical engineer the ability to analyze the wide variety of conditions commonly encountered.

RESPONSIBILITIES OF THE DISTRIBUTOR

The success of slope stability software is dependent upon several factors related to the distributor in addition to the algorithms used in the program (Christian et al, 1973; Schiffman and Jubenville, 1975; Fredlund, 1978). First, it is important that the program be written in a generally acceptable computer language that has an established standard which ensures <u>portability</u>. Portability is generally ensured when a version of FORTRAN is used that is consistent with the specifications prepared and published by the American National Standards Institute (ANSI: American National Standards Institute, 1966a, 1966b). The International Organization for Standardization (ISO) is the international counterpart and has adopted FORTRA standards which are similar to ANSI (Internation Organization for Standardization, 1972). The standards established by these organizations hav been widely accepted and should form an acceptab basis for programming.

Second, the <u>usability</u> of the program is greatly enhanced by proper documentation. The documenta tion should include sections on theory, data input, example problems and an explanation of th data output. The data input should be user-oriented. This greatly reduces the time require to get the information into the computer. Since the cost associated with data input can often exceed the cost of computing, this aspect should not be under-estimated. Attention should be giv to having some form of prompted data input. As well, attention should be given to having data verification prior to the commencement of computations. The data verification step should distinguish between "warning" and "error" situatior in the input data.

Third, the <u>credibility</u> of the program can best be established through the use of well-documente sets of example problems (Krahn and Fredlund, 1976). The example problems should be set up ir such a way as to implement a high percentage of the executable code. Credibility is also increased through extensive usage and checking of the program by a large number of engineers over a long period of time for a wide variety of applications.

Fourth, the <u>maintenance</u> of engineering computer software is an aspect which has received only limited consideration in the past. As a result most slope stability computer programs are in circulation with several different versions, each containing known errancy. Errors will be discovered from time to time in any program of considerable size and there must be an organize procedure to allow feedback of errors and subsequent implementation of program fixes for all users.

The importance of the maintenance of all softwa packages should not be under-estimated. Coatsworth and Tabb (1978) emphasized this point as follows: ". . . upkeep of the programs is a problem that arises mainly as a result of the large time intervals between successive runs of the program. There are three reasons why a pro spective user should prefer a program that is r frequently by a variety of users. Firstly, pot tial errors are more likely to have been detect Secondly, the organization has probably develop the program into a readily-used form. Thirdly, experienced support is then available. We beli that the requirement for good software is often seriously under-rated."

Fifth, slope stability computer programs requir an associated <u>education</u> effort and <u>consultation</u> The education effort is required to assist the engineering profession in the theory and the

Table 1. Features of two-dimensional slope stability programs distributed by GESA

FEATURE	[illegible]	[illegible]	BISHOP	JANBU	[illegible]
Methods of analysis	Morgenstern-Price method	Fellenius	Simplified Bishop	Janbu's generalized	Spencer
No. of strata	33	30	20	2	20
Shape of failure surface	Non-circular	Circular	Circular	Circular	Circular and non-circular
Partial submergence and tension cracks	Yes	No	Yes	No	Yes
Surcharging and benching	Yes	Yes	Yes	No	Yes
External line loads	No	No	No	No	Yes, normal to surface only Can interpolate as pressures
Earthquake loading	Yes, variable with soil type	No	No	No	No
Pore-water pressure	1 piezometric line Pore pressure coefficient r_u	10 piezometric lines Seepage force parallel to water table	Piezometric line or 1 phreatic line with seepage gradient correction	Pore pressure coefficient r_u	Pore pressure coefficient r_u Constant pressure value for a strata Interpolation of a grid of r_u or pore pressure points (68 points)
Grid designation	Individual failure surfaces designated	Search limited to 20 horizontal and 10 vertical increments	Regular x, y and radius grid	Sophisticated grid search for circular failure surface	Automatic search for circular failure surface. Individual non-circular failure surfaces
Comments	Internal forces on vertical slices output	English and SI units Calcomp and microfilm hardware plot capabilities	Cross section must have a negative slope	Cohesion changes with depth specified Anisotropic strength data	Linear variation in strength option Anisotropic soil properties
References:	Schiffman, (1975)	Leary, (1970) Hasselquist and Schiffman, (1975)	Jubenville, (1975)	Wright, (1969)	Wright, (1974)

application of the software. There must also be a system whereby a user can receive decisive advice on the operation of the program.

In the past, emphasis has been placed primarily on the generation of algorithms to compute the factor of safety while little attention has been given to the continuing support of the software. At present there appears to be a need for closer control on the condition of the software utilized.

SOFTWARE COORDINATION

Little effort has been extended to coordinate the development, dissemination and verification of computer software in the geotechnical area. As a result, most computer programs remain in an *ad hoc* status. In 1973, the Executive Committee of the International Society of Soil Mechanics and Foundation Engineering accepted an Australian proposal to establish an Institute for the Publicity and Exchange of Geomechanics Computer Programs (IPEGCP) (Aitchison, 1975). Abstracts of computer programs were published by IPEGCP without enhancement or detailed review of the program. Two slope stability programs were submitted to IPEGCP prior to the discontinuance of its functions in 1977.

In the United States, the Geotechnical Engineering Software Activity (GESA) was established in 1976 at the University of Colorado to coordinate geotechnical software. The organization made a substantial contribution in the aquisition, development and use of computer software. The collected software and the associated documentation was made available at the "cost of reproduction" (i.e., usually \$100 to \$300) to interested parties. In 1977 GESA ceased in its function of geotechnical software coordination.

Canada, as well as other countries (Dysli, 1977) have attempted to catalogue abstracts of computer programs in geotechnical engineering. This serves the purpose of publicizing the computer programs that have been developed.

Attempts at software coordination have certainly had noble objectives. However, their successes have been somewhat limited. Their objectives have included: information exchange, review, verification, distribution, enhancement, maintenance, education and development of computer software. One of the most important proposed functions (Schiffman, 1977) is the verification of a software package in order that the user "can be assured of the integrity of the program and documentation, and of its applicability to a given engineering problem." However, the verification process is very complex and lengthy. Also, certification of programs may lead to legal responsibility.

Maintenance and enhancement of software packages is extremely difficult and dangerous apart from close control by the authors of the program. Factors such as maintenance, enhancement and verification appear to be extremely important to the long-term success of a computer package and appear to best be handled by the originator with the engineering expertise. These are also costly functions and a procedure must be sought to provide the necessary financial renumeration for these functions. This can either be done through government support or through the fee-enterprise system. The approach used may differ from one country to another. However, in either case the necessary support of the program should not be disregarded.

SLOPE STABILITY SOFTWARE

Slope stability software can be divided into two broad categories. That is packages which are maintained, leased or sold on a commerical basis and those packages which are distributed at the 'cost of reproduction' with no associated maintenance or support. In the latter category, most of the significant slope stability computer programs in the United States as of 1977, were compiled by GESA. The pertinent features of two-dimensional slope stability computer programs collected by GESA are summarized in Table 1 (Fredlund, 1978). In 1975 a slope stability computer program was developed at Purdue University, U.S.A., which uses a force equilibrium factor of safety formulation (i.e., simplified Janbu method without the associated correction factor; (Siegel, 1975a; 1975b).

Several attempts to market slope stability software have been unsuccessful. This paper will not attempt to analyze the marketing difficulties in detail. However, it would appear that in general, the main difficulty has been the lack of interest in maintenance and the cost of support of the packages.

The slope stability computer packages presently being marketed are basically versions of a limited number of previously developed programs. For example, the simplified Bishop method used in several packages being marketed was originally developed at the Massachusetts Institute of Technology (MIT), U.S.A., as the LEASE subsystem of their Integrated Civil Engineering Systems (i.e., ICES) (Bailey and Christian, 1969; Hsiung and Christian, 1969). The basic features of the program are shown in Table 2. The Morgenstern-Price method used in several packages being marketed was originally developed at Imperial College, London, England and the features are essentially the same as those of the MALE program previously described (Krahn, Price and Morgenstern, 1971).

Examples of companies that are marketing slope stability software packages are McDonnell Douglas Automation Co. (MCAUTO), St. Louis, Missouri, U.S.A.; Geocomp U.K. Ltd., Bracknell, Berkshire, U.K.; Genesys Ltd., Loughborough, Leicester, England and Geo-Slope Programming Ltd., Regina, Saskatchewan, Canada. These companies distribute software worldwide. The first three companies market a combination of two programs. These are the simplified Bishop analysis for circular failure surfaces and the Morgenstern-Price method for non-circular failure surfaces. Geo-Slope Programming Ltd., markets a computer program called SLOPE-II, which was originally developed at the University of Saskatchewan, Canada (Fredlund, 1974; Fredlund, 1975). The program contains a total of six methods of analysis, all of which can be applied to either circular or non-circular (composite) failure surfaces. Table 3 summarizes some of the features of the SLOPE-II computer program.

Table 2 Features of the ICES LEASE-1 Computer Program

Feature	ICES LEASE-1
Methods of analysis	Fellenius method and simplifie Bishop method
No. of strata	Any number
Shape of failure surface	Circular
Partial submergence and tension cracks	Yes
Surcharging and berming	Yes
External line loads	No
Earthquake loading	No
Pore-water pressure conditions	Pore pressure coefficient r_u Several piezometric lines (can use both procedures during one analysis)
Grid	Specify a range for radius for a grid of centers Has a search routine
Comments	Any set of consistent units ma be used for the input of dat
Reference	Bailey and Christian, 1969 Hsiung and Christian, 1969

Table 3 Features of the SLOPE-II Computer Program

Feature	SLOPE-II
Methods of analysis	Ordinary or Fellenius Simplified Bishop Spencer Corps of Engineers Janbu's simplified Janbu's generalized Morgenstern-Price
No. of strata	15
Shape of failure surface	Circular or non-circular for all methods
Partial submergence and tension cracks	Yes
Surcharging and berming	Yes
External line loads	10 loads, any direction
Earthquake loading	Yes
Pore-water pressure	Pore pressure coefficient r_u Hilf's analysis 15 piezometric lines Grid of specified pore pressures (999) Superposition of r_u and piezometric line
Grid designation	Regular x, y and radius grid for both circular and non-circular failure surfaces
Comments	User-oriented input and flexible output Digital and Calcomp plot capabilities for geometry and factor of safety Coordinated with other programs to evaluate pore-water pressure (i.e., Finite Element and Hilf's Analysis)
Reference	Fredlund (1974, 1975)

LIST OF REFERENCES

Aitchison, G. D. (1975), "IPEGCP Abstracts," Institute for Publicity and Exchange of Geomechanics Computer Programs, Melbourne, Australia, November.

American National Standards Institute, (1966a), "USA Standard FORTRAN," United States of America Standards Institute, X3, 9-1966.

American National Standards Institute (1966b), "American National Standard Basic FORTRAN," United States of America Standards Institute, X3. 10-1966.

Bailey, W. A. and Christian, J. T. (1969), "ICES LEASE-1, A Problem Oriented Language for Slope Stability Analysis," User's Manual. Department of Civil Engineering, Massachussets Institute of Technology, Report R69-22.

Bishop, A. W. (1955), "The Use of the Slip Circle in the Stability Analysis of Slopes," Geotechnique, Vol. 5, pp. 7-17.

Bishop, A. W. (1957), "Some Factors Controlling the Pore Pressures Set Up During Construction of Earth Dams," Proceedings of the Fourth International Conference on Soil Mechanics and Foundation Engineering, London.

Chowdhury, R. N. (1978), "Slope Analysis," Developments in Geotechnical Engineering, Vol. 22," Elsevier Scientific Publishing CO., New York.

Christian, J. T., Lysmer, J. and Reti, G. A. (1973), "Engineering Computer Program Documentation Standards," ASCE Journal of the Soil Mechanics and Foundations Division, 99 (SM3).

Costsworth, A. M. and Tabb, R. (1978), Discussion of "Usage, Requirements and Features of Slope Stability Computer Software (Canada, 1977)," Canadian Geotechnical Journal, Vol. 15, pp. 435-436.

Dysli, M. (1977), "Swiss Use of the Computer in Soil Mechanics," Proceedings of the Specialty Session on Computers in Soil Mechanics: Present and Future, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, pp. 268-288.

Fredlund, D. G. (1974), "Slope Stability Analysis," User's Manual, Computer Documentation CE-4, Transportation and Geotechnical Group, Department of Civil Engineering, University of Saskatchewan, Canada, December.

Fredlund, D. G. (1975) "A Comprehensive and Flexible Slope Stability Program," Proceedings of the Roads and Transportation Association of Canada, Annual Meeting, Calgary, Alberta.

Fredlund, D. G. and Krahn, J. (1977), "Comparison of Slope Stability Methods of Analysis," Canadian Geotechnical Journal, Vol. 14, No. 3, pp. 429-439.

Fredlund, D. G. (1978), "Usage, Requirements and Features of Slope Stability Computer Software (Canada, 1977)," Canadian Geotechnical Journal, Vol. 15, pp. 83-95.

GESA, (1975), "GESA Software Abstracts," GESA Report No. Al-76-1, Geotechnical Engineering Software Activity, University of Colorado Computing Center, Boulder, CO.

Hasselquist, S. J., and Schiffman, R. L. (1975), "A Computer Program for Slope Stability: New York State and Simplified Bishop Method. SNOB-1," Version 3-A, User's Manual, GESA Report D-75-18, University of Colorado Computing Center, Boulder, CO.

Hilf, J. W. (1948), "Estimating Construction Pore Pressures in Rolled Earth Dams," Second International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Vol. III.

Horn, J. A. (1960), "Computer Analysis of Slope Stability," Journal of Soil Mechanics and Foundation Engineering, ASCE, Vol. 86, No. SM3, pp. 1-17.

Hsiung, C. C. and Christian, J. T. (1969), "Extended LEASE-1, An ICES Subsystem," Final Report, MIT Soils Publication, No. 234, Massachusetts Institute of Technology, Cambridge, MA.

International Organization for Standarization (1972), "ISO Recommendations R1539, Programming Language FORTRAN," ISO/R 1539-1972 (E).

Jubenville, D. M. (1975), "A Computer Program for Slope Stability, Modified Bishop Method, Version 1-A BISHOP-1," User's Manual, GESA, University of Colorado Computing Center, Boulder, CO.

Krahn, J., Price, V. E. and Morgenstern, N. R. (1971), "Slope Stability, Computer Program for Morgenstern-Price Method of Analysis," User's Manual No. 14, University of Alberta, Edmonton, Alberta.

Krahn, J. and Fredlund, D. G. (1976), "Evaluation of the University of Saskatchewan Slope Stability Program," Presented at the Roads and Transportation Association of Canada, Quebec City, Quebec, Canada.

Krahn, J., Johnson, R. F., Fredlund, D. G. and Clifton, A. W. (1979), "A Highway Cut Failure in Cretaceous Sediments at Maymont, Saskatchewan," Canadian Geotechnical Journal, Vol. 16, No. 4.

Little, A. L. and Price, V. E. (1958), "The Use of an Electronic Computer for Slope Stability Analysis," Geotechnique, Vol. 8, No. 3, September, pp. 113-120.

Roberts, L. G. and Wessler, B. D. (1970), "Computer Network Development to Achieve Resource Sharing," American Federation of Information Processing Societies Conference Proceedings, Spring Joint Computer Conference, 36, pp. 543-549.

Schiffman, R. L. and Jubenville, D. M. (1975), "Computer-based Technology Transfer in Geomechanics," Preprint 2613, ASCE National Convention, Denver, Colorado, November 3-7.

Schiffman, R. L. (1975), "A Computer Program to Analyze the Stability of Slopes by Morgenstern's Method, MALE-1, Version 2-A," User's Manual, GESA Report D-75-16, University of Colorado Computing Center, Boulder, CO.

Schiffman, R. L. (1977), "Computers in Soil Mechanics: Present and Future," Proceedings of the Speciality Session on Computers in Soil Mechanics: Present and Future, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, MAA Publishing CO., pp. 1-28.

Siegel, R. A. (1975), "Computer Analysis of General Slope Stability Problems," JHRP-75-8, Joint Highway Research Project No. C-36-36K, Engineering Experimental Station, Purdue University, West Lafayette, Indiana, June, pp. 1-112.

Siegel, R. A. (1975), "STABL2 User's Manual," JHRP-75-9, Joint Highway Research Project No. C-36-36K, Engineering Research Station, Purdue University, West Lafayette, Indiana, June, pp. 1-103.

Whiteman, R. V. and Bailey, W. A. (1967), "Use of Computers for Slope Stability Analysis," Journal of Soil Mechanics and Foundation Engineering, ASCE, Vol. 93, No. SM4, pp. 519-541.

Wright, S. G. (1969), "A Study of Slope Stability and the Undrained Shear Strength of Clay Shales," Ph.D. thesis, University of California, Berkeley, CA.

Wright, S. G. (1974), "SSTAB1-A General Computer Program for Slope Stability Analyses," Research Report No. GE-74-1, Department of Civil Engineering, University of Texas at Austin, Austin, TX.