8-1999

Computer assisted analysis of rock slope stability

Joshua Hugh Cole

To the Graduate Council:

I am submitting herewith a thesis written by Joshua Hugh Cole entitled "Computer assisted analysis of rock slope stability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Matthew Mauldon, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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Matthew Mauldon, Major Professor

We have read this thesis
and recommend its acceptance:

Eric C. Drumm

Richard M. Bennett

Accepted for the Council:

Associate Vice Chancellor and
Dean of the Graduate School

COMPUTER ASSISTED ANALYSIS OF ROCK SLOPE STABILITY

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Joshua Hugh Cole
August 1999

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ABSTRACT

Computers provide a powerful tool for the stability analysis of many physical scenarios. An area where advanced interactive computer analysis software has been relatively sparse is in the analysis of rock slopes. Interactive software aids in the analysis of rock slope stability in two main ways: first, by automating long and involved calculations, thus saving time and minimizing human error and second, by providing rapid visual feedback on how changing input parameters affects stability. In this way, the rock slope engineer can quickly get a feel for the factors critical to the problem at hand and the software thus becomes an effective learning tool, in addition to being an analysis tool.

Three interactive computer programs which aid in the stability analysis of rock slopes have recently been developed at the Institute for Geotechnology, University of Tennessee, Knoxville under a research project funded by the Tennessee Department of Transportation. These programs are entitled *PlaneSlip*, *WedgeSlip*, and *RockSlip* and are collectively known as the *ROCKSLIP* package. *PlaneSlip* and *WedgeSlip* implement limiting equilibrium solutions for plane and wedge slides, respectively, while *RockSlip* implements an energy method to analyze the stability of curved or multi-plane failure surfaces. Application of these programs to the analysis of rock slopes in East Tennessee and Alabama will be demonstrated with some worked example problems. The worked examples are also included in a workbook which gives a condensed introduction to the programs and highlights major features of the programs with each of the example problems.

These programs allow the user to interactively adjust the discontinuity geometry, slope geometry, water pressure, friction angle, cohesion, and slope reinforcement. Water pressure in *PlaneSlip* and *RockSlip* is governed by the combination of two parameters: the height of water in a tension crack and a parameter called drainage impedance, which controls the permeability of the discontinuities. In *WedgeSlip* there is an input value for the average water pressure on each plane which can be specified by the user or set to a default value based on slope geometry. Screen displays of the slope cross section and stereographic projections of the slope geometry and discontinuity data change in real time as the user adjusts the variables.

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PART I

INTRODUCTION

Introduction

The incorporation of computers into analysis of rock slopes achieves several useful and effective goals. First, computers can perform thousands of calculations in a matter of seconds, thus easing the need for tedious hand calculations and reducing the probability of human error. Second, the ability to observe the effects of changes in input parameters on slope stability as they are modified makes computer analysis a highly effective learning tool. The value of "real-time" learning cannot be underestimated. It can easily illustrate, even to a beginner, the basic effects that parameters like friction angle and water pressure have on slope stability.

Three computer programs have recently been developed at the University of Tennessee, Knoxville. They are entitled *PlaneSlip*, *WedgeSlip*, and *RockSlip* and are collectively known as the *ROCKSLIP* Package. *PlaneSlip* and *WedgeSlip* use limiting equilibrium methods to analyze plane and wedge failures, respectively. *RockSlip* uses an energy-based approach developed by Mauldon and Ureta (1996) and Mauldon et. al. (1998) to analyze failures on curved or multi-planar failure surfaces. Visual Basic 5.0 Professional Edition© has been used to develop the most recent versions of the programs. The use of this 32-bit developing environment has allowed a compact and eye-pleasing design for all the programs. Another goal in designing these programs has been the implementation of "real-time learning" features through the auto-redraw function (found in *PlaneSlip* and *WedgeSlip*). This thesis summarizes the work done on this project and describes the three computer programs. A User's Guide with step-by-step instructions and a worked example is included for each program.

PlaneSlip and *WedgeSlip* both have "real-time" user interfaces which enables one to look at how changes in slope geometry and mechanical parameters affect the stability of a slope. *RockSlip* lets the user import an image of a slope and then define the failure surfaces and outcrop parameters to be analyzed.

One of the major objectives undertaken when these programs were being written was to gain a better understanding of the role of water pressure in failures. While water pressure is rather hard to characterize, its effects cannot be ignored or underestimated. Water pressure depends highly on the permeability of the discontinuities and their infilling material (if present). Another factor is the drainage conditions at the toe of the failure surface(s). This factor is controlled in the programs by a parameter entitled "drainage impedance." Drainage impedance (ξ) can be seasonally dependent. For example, it can become greater in the winter when water freezes near the surface outcrop of a discontinuity and lessen in the summer as the ice melts and allows free drainage.

The original impetus behind this project was the need to implement a new rock slope stability analysis method for slopes consisting of folded rock geometries. Since the failure surface in such cases can be regarded as a series of m planes ($m > 2$), limiting equilibrium analysis yields an indeterminate answer for these slopes. A method based on potential energy was developed for stability analysis in folded rocks. This analysis technique was adapted into the computer program entitled *RockSlip*. As time progressed, programs to analyze other basic rock slope geometries were developed. *WedgeSlip* and *PlaneSlip* were the results of this effort.

PART II

PLANESLIP

VERSION 1.3

USER'S GUIDE

A computer program for the analysis of planar rock slope failures.

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CHAPTER 2.1 INTRODUCTION

2.1.1 Program Development

PlaneSlip Version 1.3 was developed by The Institute for Geotechnology, Department of Civil and Environmental Engineering, The University of Tennessee at Knoxville as part of a research project for the Tennessee Department of Transportation. The program authors are Dr. Matthew Mauldon, You Li, Yen-Yit Chan and Joshua Cole. Any questions or comments about *PlaneSlip* should be addressed to:

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http://www.engr.utk.edu/research/geo/institute

2.1.2 Disclaimer

The authors disclaim any responsibility for the correctness of the data generated by the *PlaneSlip* package, or for the consequences resulting from the use thereof. Any use or misuse of this package is the sole responsibility of the user.

2.1.3 Program Features

This guide has been developed to help users understand and operate the *PlaneSlip* program. *PlaneSlip* was developed using a simple model of a plane failure situation. The stability analysis is performed on the basis of limiting equilibrium, following the discussion of plane slides in the book *Rock Slope Engineering* (Hoek & Bray, 1981) with several additional developments. Since plane failure does not involve complex three-dimensional modeling, it is relatively easy to investigate the sensitivity of a rock slope to factors such as water pressure or shear strength of the discontinuity. With this fact in mind, some major features included in *PlaneSlip* should be brought to the user's attention.

- **Auto-Redraw** - The *auto-redraw* function enables the user to change key parameters and see, in "real-time", how these changes affect the slope's stability.
- **Water Level** - The height of water in the tension crack controls the magnitude of water pressure acting on the slope.
- **Drainage Impedance** - A parameter entitled "drainage impedance" has been incorporated into the program. This allows the user to change the pressure distribution behind the slope by varying the drainage conditions along the sliding plane and at the toe of the slope.
- **Rockbolts** - The effects of rock reinforcement (rock anchors or rockbolts) are also included in *PlaneSlip*. Parameters such as number, orientation, tensile and shear capacity, minimum embedment length and horizontal spacing can be defined for the rock reinforcement.

- **Tension Crack Angle** - The angle of the tension crack can also be adjusted. This is a feature that has not been included in much of the previous work on rock slopes (e.g., Hoek & Bray, 1981).
- **Y2K Compliant** - *PlaneSlip* includes no reference to date and is therefore fully Y2K compliant.

2.1.4 Program Installation

PlaneSlip is compatible with *Windows 95/98/NT*. Approximately 3MB of free hard drive space is required to install the program. There are two 3 ½" floppy disks included for the setup of *PlaneSlip*. Insert the disk labeled "Setup Disk 1 of 2" into the floppy disk drive (usually labeled drive a: or b:). Click on the **Start** button, go to **Run** and type in "a:\setup.exe" (or "b:\setup" depending on your drive letter). Then simply follow the instructions that appear on your screen to setup *PlaneSlip*.

CHAPTER 2.2 THEORY

2.2.1 Geometric Constraints

The following geometric criteria (from Hoek & Bray, 1981) are necessary conditions for plane failures:

- The plane on which sliding occurs must strike parallel or nearly parallel (within approximately $\pm 20°$) to the slope face.
- The failure plane must "daylight" in the slope face. This means that its dip must be less than the dip of the slope face.

- The dip of the failure plane must be greater than the angle of friction of this plane (in the absence of water pressure or other additional loads).
- Release surfaces which provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide. Alternatively, failure can occur on a failure plane passing through the convex "nose" of a slope.

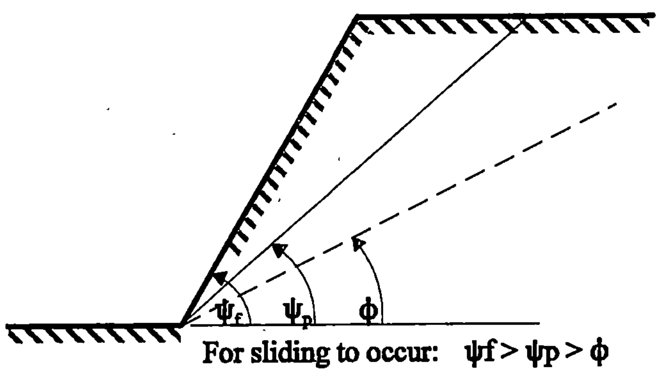

Figure 2.1 Generalized cross-section of a planar rock slope showing some geometric requirements for plane sliding.

Figure 2.1 shows a generalized cross-section of a planar rock slope, where ψ_f = dip of slope face, ψ_p = dip of sliding plane, and ϕ = friction angle of discontinuity.

Figure 2.2 on the following page shows some of the slope geometries that are possible in *PlaneSlip*.

2.2.2 Analysis Assumptions

The following assumptions are made for the analysis of a plane slide. All are based on Hoek & Bray (1981), except for the assumption concerning water pressure:

- The sliding surface and the tension crack strike parallel to the slope surface.

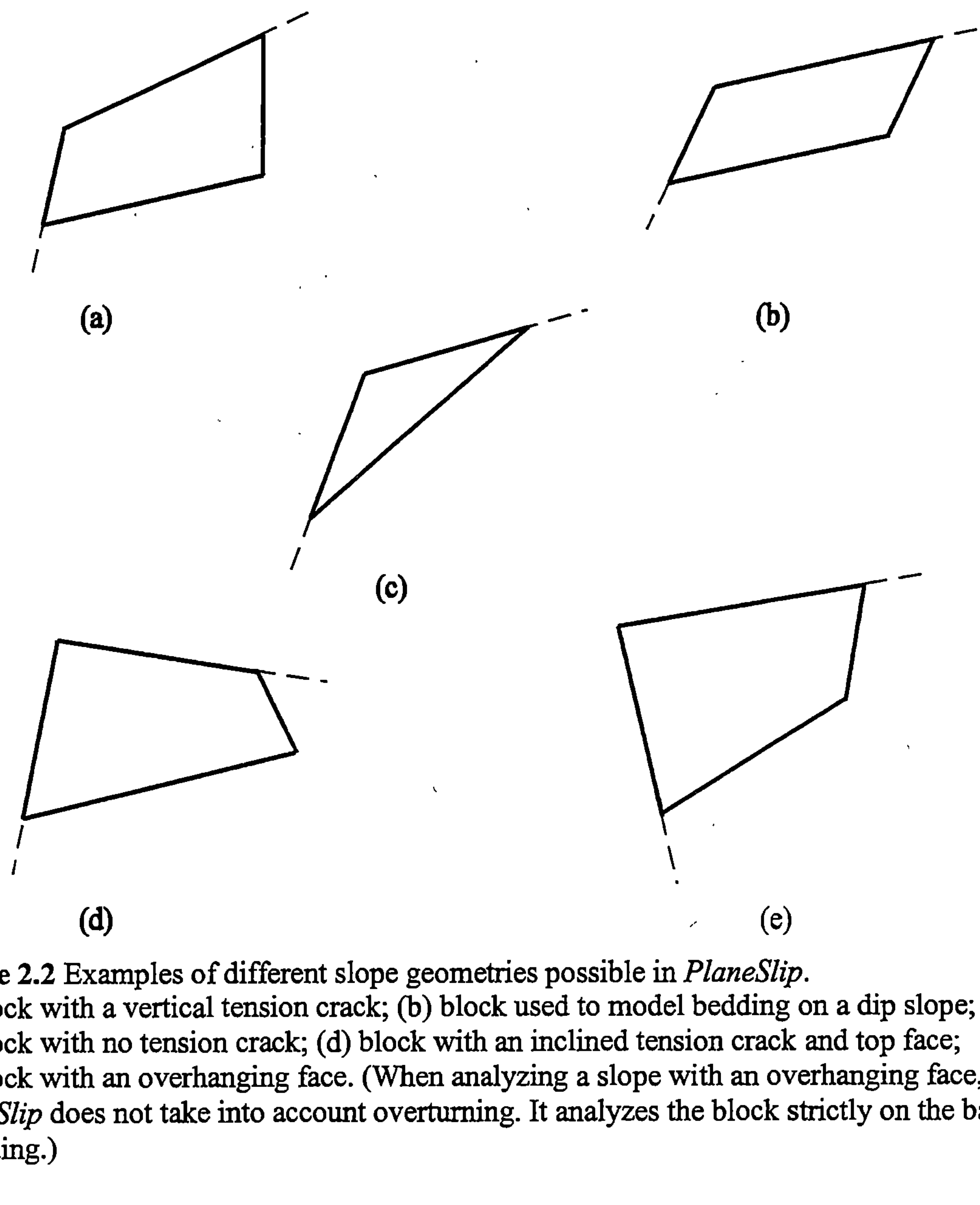

Figure 2.2 Examples of different slope geometries possible in *PlaneSlip*.
(a) block with a vertical tension crack; (b) block used to model bedding on a dip slope; (c) block with no tension crack; (d) block with an inclined tension crack and top face; (e) block with an overhanging face. (When analyzing a slope with an overhanging face, *PlaneSlip* does not take into account overturning. It analyzes the block strictly on the basis of sliding.)

- Water enters the sliding surface along the base of the tension crack and seeps along the sliding surface, escaping at atmospheric pressure where the sliding surface daylights in the slope face. This is the case when there is no drainage impedance at the toe of the slope. If drainage is impeded then the water pressure distribution on the sliding surface is modified according to the amount of impedance. See Figures 2.3a & b for a graphical representation of the two cases.
- All forces are assumed to act through the centroid of the sliding mass. This implies that there are no moments created by the forces acting on the block. This assumption is not the case in most plane slides, but the error introduced by ignoring the moments is negligible (Hoek & Bray, 1981).
- The shear strength of the sliding plane is defined by the Mohr-Coulomb criterion:

$$\tau_f = c + \sigma_f' \tan\phi \qquad \textbf{(2.1)}$$

  where τ_f = shear stress at failure, c = cohesion, σ_f' = effective normal stress at failure, and ϕ = friction angle.
- A slice of unit thickness is considered and it is assumed that release surfaces are present so that there is no resistance to sliding at the lateral boundaries of the failure.

2.2.3 Water Force

The water force is calculated in three separate parts depending on the conditions at the toe of the slope. If the toe is free to drain, the water pressure distribution is that shown in Figure 2.3a (note that z_w is the depth of water in the tension crack). If drainage at the toe of the slope is completely impeded then the pressure head continues to increase with depth and the pressure distribution is the same as the free draining case with an additional triangular pressure block acting perpendicular to the sliding plane (Figure 2.3b). If drainage at the toe of the slope is partially impeded then the pressure distribution will vary based on the amount of drainage impedance. An intermediate pressure distribution is shown in Figure 2.3c. If water reaches atmospheric pressure at a point back into the slope along the slide plane then the water pressure distribution will be like that shown in Figure 2.3d. Negative drainage impedance is used to model this scenario which may occur if the slide plane has become eroded or opened near the toe of the slope causing water to reach atmospheric pressure before it reaches the toe of the slope. The amount of negative drainage impedance is used to determine the point along the slide plane where the pressure distribution goes to zero. For instance, if the drainage impedance is negative 50%, then the distribution will go to zero at a point halfway along the sliding plane.

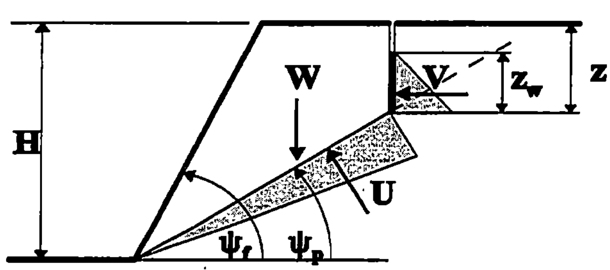

Figure 2.3a Generalized cross-section of a plane slide with no drainage impedance at the toe of the slope.

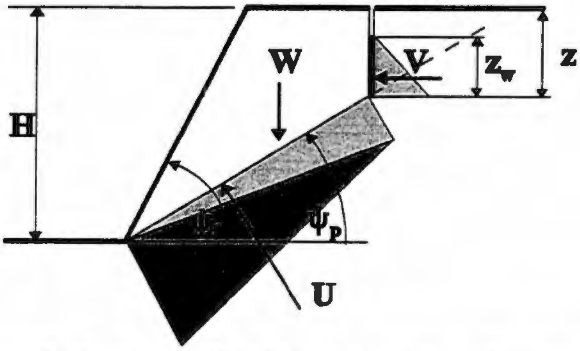

Figure 2.3b Generalized cross-section of a plane slide showing assumed water pressure distribution with complete drainage impedance at the toe of the slope.

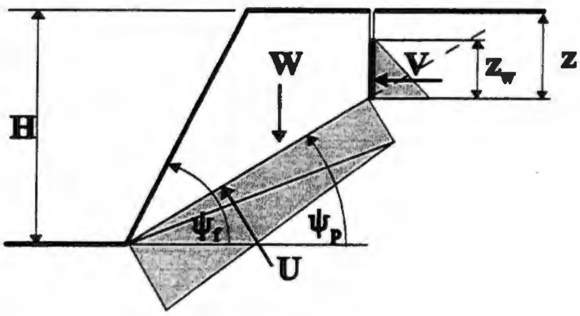

Figure 2.3c Generalized cross-section of a plane slide showing assumed water pressure distribution with partial drainage impedance at the toe of the slope.

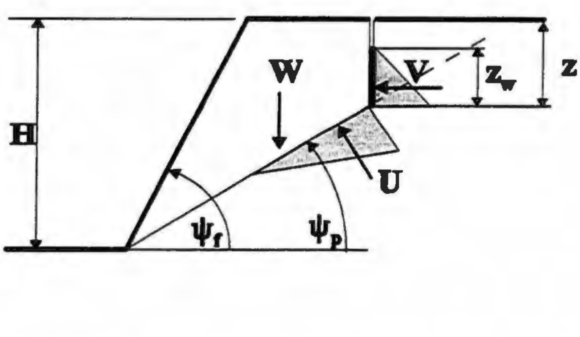

Figure 2.3d Generalized cross-section of a plane slide showing assumed water pressure distribution with negative drainage impedance.

2.2.4 Rockbolts

PlaneSlip considers rockbolt reinforcement based on the number, spacing, capacity and orientation of the bolts, all of which are input by the user. The orientation of the rockbolts is defined by the angle, θ, that the rockbolts make with the normal to the face. This angle is easily measured in the field and is also the type of information that needs to be conveyed to a driller who is installing the rockbolts. Note that this angle can be positive or negative depending on its orientation with respect to the slope face normal. However, in calculations it is easier to use the angle, β, the bolts make with the normal to the failure plane (see Figure 2.4). Note that β can be calculated indirectly from the dips of the face and failure plane and the angle, θ. For rockbolts installed in the face (e.g. Fig 2.4), β is given by:

$$\beta = \psi_f - \psi_p - \theta \qquad (2.2)$$

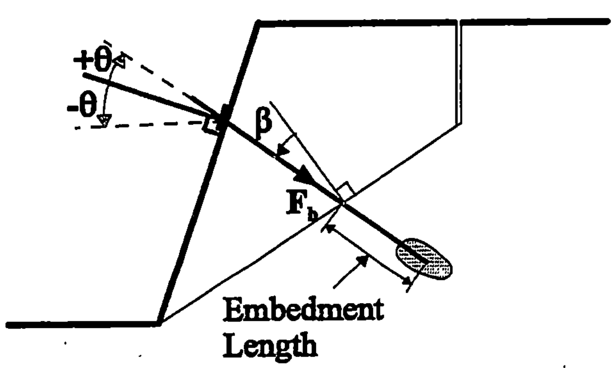

Figure 2.4 Plane slide schematic defining the orientation of a rock bolt or cable.

Another common practice for specifying the orientation of a rockbolt is using the plunge (i.e. the angle that the downward direction of the bolt makes with horizontal). When defining the orientation of a line, or in this case the bolt axis, using plunge and trend it is standard to take the trend as the downward direction of the bolt. To calculate θ from a specified rockbolt plunge and trend the following equations (two cases) should be used (both in degrees):

Case 1: The rockbolt trend is equal to the slope face dip direction.

$$\theta = \psi_f - 90 - \text{plunge} \tag{2.3}$$

Case 2: The rockbolt trend is equal to the slope face dip direction + 180°.

$$\theta = \psi_f - 90 + \text{plunge} \tag{2.4}$$

In *PlaneSlip*, rockbolts are shown penetrating the slope face first and then the failure plane (See Figure 2.5). Embedment length is the length of rockbolt that goes beyond the sliding plane. The user specifies the minimum embedment length (Figs 2.4 and 2.5). If a bolt embedment length is less than the specified minimum, it is drawn as a dashed line and omitted from the stability calculations. Vertical spacing of the bolts is calculated by dividing the height of the slope face by the number of bolts. *PlaneSlip* automatically assumes uniform vertical spacing of the bolts in the face with the top and bottom bolts being half the vertical spacing distance from the crest and toe of the slope, respectively.

If rockbolts are to be installed in the top face of the slope, β will be related to θ by a different equation.

$$\beta = \psi_t - \psi_p - \theta \tag{2.5}$$

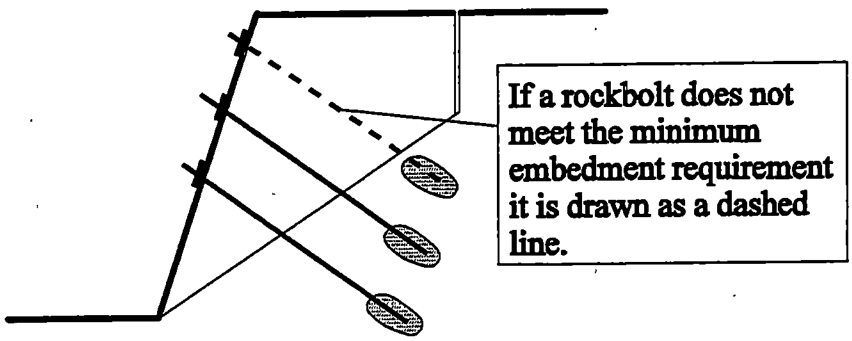

Figure 2.5 Plane slide schematic showing the number of rockbolts.

All quantities are the same except for ψ_t, which is the dip of the top face instead of the front face. *PlaneSlip* only shows rockbolts which penetrate the slope face, but rockbolts in the top face can be modeled accurately as bolts in the slope face by ensuring that β is the correct value (Figure 2.6). This requires some caution when entering the value for θ. First calculate β based on the assumption that the rockbolts will be in the top face (i.e. use equation 2.3). Then insert this value into equation 2.2 to obtain the proper input value for θ.

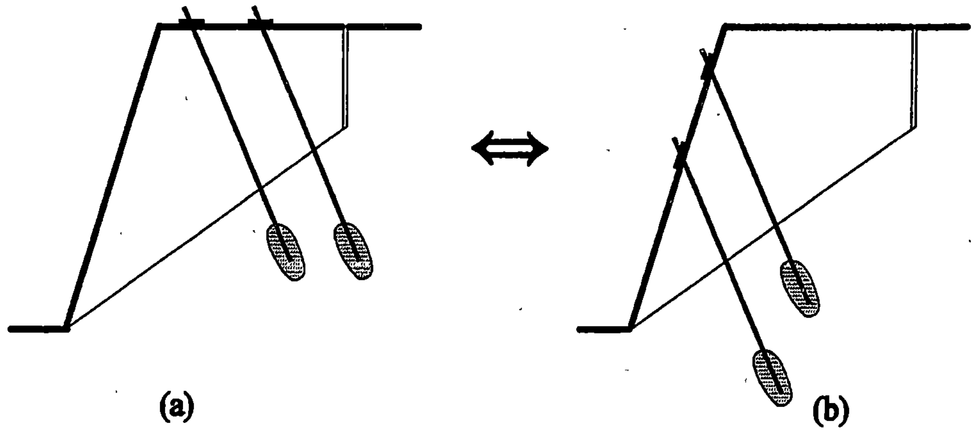

Figure 2.6 (**a**) Rockbolts in the top face equivalent to
(**b**) Rockbolts in the slope face.

2.2.5 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. Thus, one must define an index which describes the relationship between driving and resisting forces for each geometric and mechanical situation in a rock slope. This is traditionally done using an index called the *Factor of Safety*, defined as the ratio of the total resisting force to the total driving force. For plane sliding with no reinforcement, the equation for calculating the FS is as follows (Hoek & Bray, 1981). See Table 2.1 for definition of variables.

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi}{W\sin\psi_p + V\cos\psi_p} \qquad (2.6)$$

The above equation includes the effects of water pressure but does not address the effects of rock reinforcement. If rockbolts or cables are oriented as shown in Figure 2.3, then the equation is modified as follows. See Table 2.1 for definition of variables.

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p + N_b F_b \cos\beta)\tan\phi + (N_b S_b / S_h)}{W\sin\psi_p + V\cos\psi_p - N_b F_b \sin\beta} \quad \textbf{(2.7)}$$

Table 2.1 Definition of Variables		
Variable	**Description**	**Figure**
FS	Factor of safety	N/A
c	Cohesion	N/A
A	Area of failure surface	N/A
W	Weight of sliding mass	Figure 2.3a-d
ψ_p	Dip of failure plane	Figure 2.1
U	Uplift water force on failure plane	Figure 2.3a-d
V	Water force on tension crack	Figure 2.3a-d
ϕ	Friction angle	Figure 2.1
N_b	Number of rockbolts with embedment length greater than the minimum.	N/A
F_b	Tensile force in rockbolts	Figure 2.4
β	The angle the bolts make with the normal to failure plane	Figure 2.4
S_b	Shear strength of rockbolts	N/A
S_h	Horizontal spacing of rockbolts	N/A

2.3.1 Input Parameters

The following parameters can be input and edited by the user. Most of the parameters can be found in the variables diagram (Figure 2.7). A brief description, the units of measurement and range of values are given for each parameter in Table 2.2.

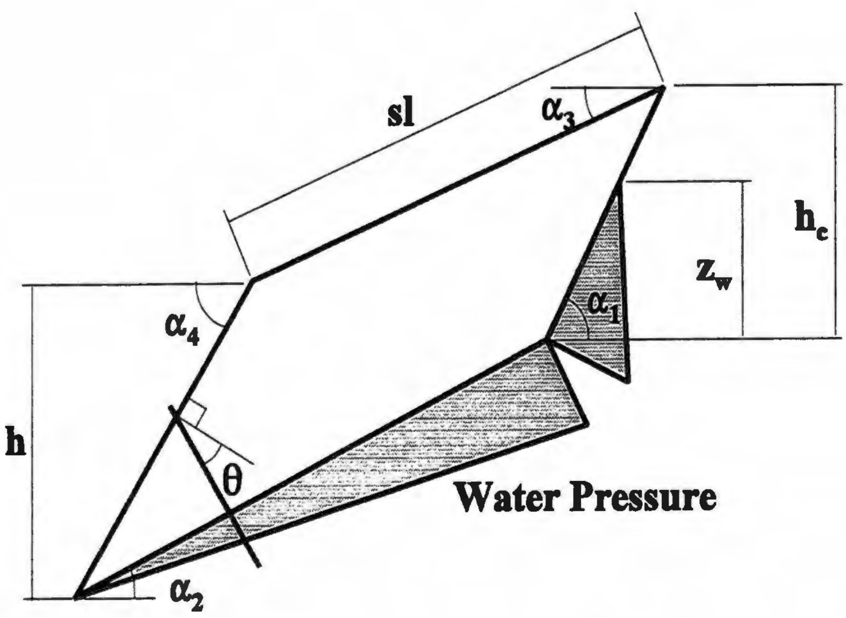

Figure 2.7 *PlaneSlip* Variables Diagram

Table 2.2 Definition of Input Parameters for *PlaneSlip*.

Parameter	Description	Figure	Units of Measurement	Range
h	Height of slope face.	Fig 2.7	Meters or feet	0 to ∞
sl	Length of upper slope.	Fig 2.7	Meters or feet	0 to ∞
α1	Dip of tension crack.	Fig 2.7	Degrees	0 to 180
α2	Dip of sliding plane.	Fig 2.7	Degrees	1 to 180
α3	Dip of upper slope.	Fig 2.7	Degrees	-90 to 90
α4	Dip of slope face.	Fig 2.7	Degrees	0 to 180
ϕ	Friction angle of sliding plane.	Fig 2.1	Degrees	0 to 180
c	Cohesion of sliding plane.	N/A	kPa or psf	0 to ∞
z_w	Water level in tension crack.	Fig 2.7	Meters or feet	0 to h_c
γ	Unit weight of the rock mass.	N/A	kN/m^3 or pcf	0 to ∞
ξ	Drainage Impedance. Parameter which describes the drainage conditions at the toe of the slope. 0% = fully drained toe, 100% = no drainage at the toe.	Fig 2.3b	Percentage - %	-90 to 100
N_b	Number of rock bolts in cross-section.	N/A	N/A	0 to ∞
L_b	Length of rockbolts.	N/A	Meters or feet	0 to ∞
θ	Angle rockbolts make with normal to the slope face.	Fig 2.4	Degrees	-90 to 90
F_b	Axial force in rockbolts.	Fig 2.4	kN or kips	0 to ∞
S_h	Horizontal spacing of rockbolts.	N/A	Meters or feet	1 to 60

Parameter	Description	Figure	Units of Measurement	Range
ME	Required embedment length.	Fig 2.4	Meters or feet	1 to 30
S_b	Shear capacity of rockbolts.	N/A	kN or kips	0 to ∞

2.3.2 Display Options

The following options are located in the pull-down menu labeled "Display" at the top of the screen.

Show Variables Diagram - (on by default) Allows user to choose whether or not to view the variables diagram. When activated, the variables diagram appears in a fixed position centered at the top of the picture box.

Enable Auto-Redraw Feature - (on by default) When this feature is enabled, the user can edit any of the parameters and see the immediate effects that they have on the cross section and/or factor of safety. Note that if this feature is not enabled then the *Update Screen* button must be used to recalculate the factor of safety and redraw the cross-section for each change in input.

Save as Bitmap... - Allows the user to save the diagram that is currently displayed in the window as a bitmap. This command calls up a dialog box which allows the user to select a filename and directory to save the bitmap under.

Note that the user can also capture the currently active form and insert it into a document. Once the form you want to insert is on the screen and active, press Alt + Print

Screen. This will capture the form. Then go to your document and select Paste to insert the image where you want it.

2.3.3 Picture Controls

The following controls are located in the lower left hand corner of the picture box.

Zoom In (+) - Allows the user to enlarge the size of the cross-section in the picture box.

Zoom Out (-) - Allows the user to decrease the size of the cross-section in the picture box.

Clear (C) - Clears the current cross-section out of the picture box. Note that this does not remove the variables diagram from the picture box. The *Show Variables Diagram* option, located under the "Display" pull-down menu, is used to toggle the visibility of the variables diagram.

Directional Buttons (horizontal and vertical scroll bars) - The directional buttons are used to move the cross-section around within the picture box.

Reset Button (R) - The reset button returns the cross-section to its original position in the picture box.

2.3.4 Command Button

Update Screen - The "Update Screen" button is located directly below the picture box. If the *auto-redraw* function is not enabled, this button is used to command the program to redraw the cross-section using the current input and to recalculate the factor of safety based on the current input.

2.3.5 File Options

The following file options are located in the "File" pull-down menu.

Open - Allows the user to open and edit a file containing previously saved data.

Close - Closes the currently opened data file.

Save as - The user can save input data in a text file of their choice. These data files can then be recalled for use in calculations.

Print - Prints the current program display as seen on the screen.

Exit - Exits the program.

2.3.6 Data

These options can all be found under the "Data" pull-down menu.

Units of Measurement - *PlaneSlip* allows for the use of two different measuring systems, fps (English) and SI (Metric). When the units of measurement are changed at run-time, the program will convert each value to the appropriate unit system.

Typical Mechanical Parameters - PlaneSlip includes some common values for rock unit weight, discontinuity friction angle and rockbolt axial and shear force in the "Data" pull-down menu.

Examples - There are also three example files that can be found under the "Data" pull-down menu. Example number one is from a limestone quarry, the second from a TRB special report (Turner and Schuster, 1996) and the last from Hoek and Bray's discussion of plane failures. Clicking on any of these examples automatically inserts the appropriate data and calculates the factor of safety.

2.3.7 Interpretation of Output

The main form of output in the *PlaneSlip* interface is the factor of safety display, located just below the picture box. The picture box also serves as a major source of output because it presents the cross-section. The variables diagram is optionally displayed in the picture box.

Factor of Safety - The common output of the program. Displays the calculated factor of safety for the current input if the auto-redraw function is enabled. If the auto-redraw function is disabled, displays the factor of safety for the data which was on the screen when the *Update Screen* button was last selected.

2.3.8 Worked Example

This example is based on field work done in a limestone quarry in Alabama. The input data are shown in Figure 2.8. The example presented here corresponds with the example used in *WedgeSlip*.

Step 1. Accessing Data - To access the example data (shown in Figure 2.8) go to the pull-down menu labeled "Data". Under that menu there will be a submenu entitled "Examples". Within that submenu there are several examples listed. Choose Example 1 (Limestone Quarry).

Step 2. Program Appearance - When the example first appears on the screen, the factor of safety should be equal to one and the maximum water level equal to 4.65 meters. Go to the "Display" pull-down menu and turn off the variables diagram. A diagram showing a cross-section of the slope should appear. Figure 2.8 shows how your screen should look immediately after opening Example 1. You may want to center and enlarge the cross-section drawing at this point. Center the diagram using the directional buttons. To enlarge, simply click on the zoom button located in the lower left corner of the picture box. The cross-section should enlarge in regular increments each time the button is clicked.

Step 3. Slope Geometry - Examine the effects that changing slope geometry have on the cross-section, and more importantly, on the factor of safety. For example, adjust the value for the face height, *h* (initially set to 10 meters), through a range of values and see how this affects the slope geometry and stability.

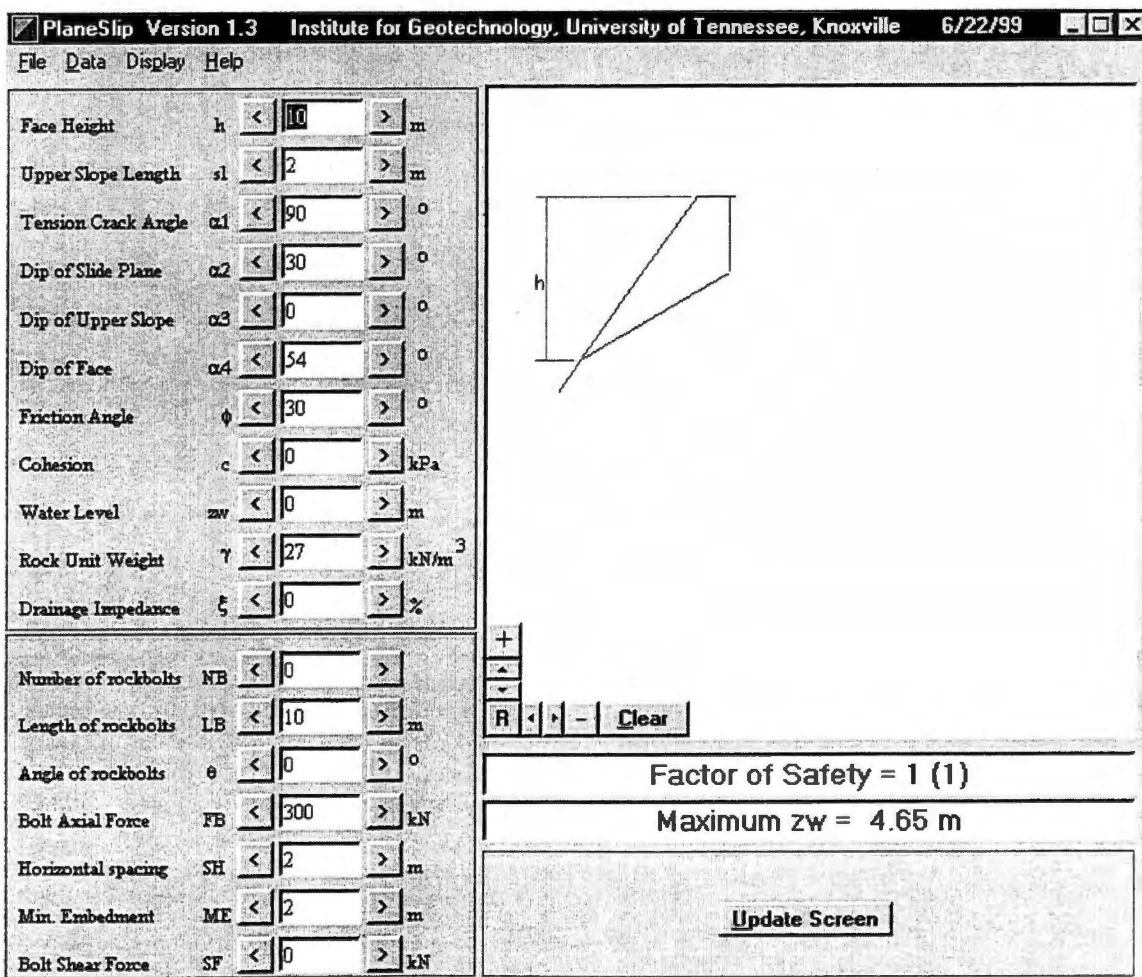

Figure 2.8 Example 1 output screen as it appears in *PlaneSlip*.

Step 4. Mechanical Parameters - Now change some of the mechanical parameters of the slope (i.e. friction angle, cohesion, unit weight). You should find that the slope's stability is least sensitive to unit weight and most sensitive to changes in the friction angle. To demonstrate this change the friction angle from its default value of 30 to 20. The factor of safety should drop from 1 to 0.63.

Step 5. Water Pressure - Examine the effects of water pressure. As the water level is increased from zero, the factor of safety should decrease. If one exceeds the maximum water level, a message saying "Maximum water level exceeded!" should appear. Try adjusting the drainage impedance. The water pressure distribution (shown on the cross-section in blue) should change according to the changes made in water level and drainage impedance. For instance, if the water level increases, an overall increase in the size of the pressure distribution should be seen. If the drainage impedance is raised, one should note a marked increase in the pressure distribution near the toe of the slope.

Step 6. Rockbolts - Now add reinforcement to the slope by changing the value for N, the number of rockbolts. Note any bolts that appear as a dashed line. This means they are not long enough to meet the minimum embedment requirement and are not included in the stability calculations. Try varying the axial and shear force, orientation and horizontal spacing of the rockbolts. There are preset values for the rockbolt axial force located in the "Data" pull-down menu. They are located under the "Typical rockbolt parameters" submenu. The values are based on the post-tension stress or 60% of the ultimate strength of the bolt. As the strength of the bolts is increased, so should the factor of safety. As the horizontal spacing is increased, the factor of safety should decrease.

2.3.9 Troubleshooting

The factor of safety display has several comments that are shown under certain conditions. The following is a summary of those possible outputs with a brief explanation of the cause of each output.

Data Entry Wrong - Occurs when the calculated length of the tension crack is less than zero. Caused by erroneous slope geometry inputs.

Driving Force Acting Against Sliding (factor of safety not defined) - Occurs when the calculated driving force is equal to or less than zero. This creates a problem since the factor of safety equation will result in a division by zero. This error can be caused by excessive water force acting on the sliding plane. It can also be a result of erroneous slope geometry.

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PART III

WEDGESLIP

VERSION 1.3

USER'S GUIDE

A computer program for the analysis of wedge failures in rock slopes.

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List of Figures

CHAPTER 3.1 INTRODUCTION

3.1.1 Program Development

WedgeSlip Version 1.3 was developed by The Institute for Geotechnology, Department of Civil and Environmental Engineering, The University of Tennessee at Knoxville as part of a research project for the Tennessee Department of Transportation. The program authors are Dr. Matthew Mauldon, You Li, Yen-Yit Chan and Joshua Cole. Any questions or comments about *WedgeSlip* should be addressed to:

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http://www.engr.utk.edu/research/geo/institute

3.1.2 Disclaimer

The authors disclaim any responsibility for the correctness of the data generated by the *WedgeSlip* package, or for the consequences resulting from the use thereof. Any use or misuse of this package is the sole responsibility of the user.

3.1.3 Program Features

The following guide has been developed to help users understand and operate the *WedgeSlip* program. *WedgeSlip* was based on a wedge failure model devised by Hoek & Bray (1981), with further developments. The mechanics of a wedge failure are analyzed using limiting equilibrium theory. Since a wedge failure involves the interaction of several discontinuities and bounding surfaces, it is often difficult to visualize what a particular slope may look like. WedgeSlip has several features which aid the user in understanding slope geometry and modeling the slope as accurately as possible.

- **Graphical Output** - *WedgeSlip* incorporates several diagrams (including upper and lower hemisphere stereographic projections, cross section and variables diagram) which aid the user in grasping the physical scenario.
- **Auto-Redraw** - When used in conjunction with the *auto-redraw* feature, the above mentioned diagrams can serve as powerful learning tools. The *auto-redraw* feature can also be used to perform sensitivity analyses since it provides real-time output for each subtle change in geometric or mechanical parameters.
- **Rockbolts** - *WedgeSlip* allows for the addition of rock bolt or cable reinforcement. Parameters such as number, tensile and shear capacity and minimum embedment length can be defined for the rock reinforcement.
- **Water Pressure** - The effects of water pressure on wedge stability are accounted for with average water pressure parameters (one value for each plane). For a detailed explanation of the water pressure calculation see Part 7.

- **Units of Measurement** - *WedgeSlip* allows for the use of two different measuring systems, fps (English) and SI (Metric). When the units of measurement are changed at run-time, the program will convert each value to the appropriate unit system.
- **Examples** - Five example problems are also included under the pull-down menu "Data", which are based on published results.
- **Y2K Compliant** - *WedgeSlip* includes no reference to date and is therefore fully Y2K compliant.

3.1.4 Program Installation

WedgeSlip is compatible with *Windows 95/98/NT*. Approximately 3MB of free hard drive space is required to install the program. There are two 3 ½" floppy disks included for the setup of *WedgeSlip*. Insert the disk labeled "Setup Disk 1 of 2" into the floppy disk drive (usually labeled drive a: or b:). Click on the **Start** button, go to **Run** and type in "a:\setup.exe" (or "b:\setup" depending on your drive letter). Then simply follow the instructions that appear on your screen to setup *WedgeSlip*.

CHAPTER 3.2 THEORY

3.2.1 Wedge Geometry

The geometry of a wedge, for the purpose of analyzing the basic mechanics of sliding, is defined in Figures 3.1 and 3.2. Some cases involve large, through-going fractures creating a single wedge which may fail in a violent manner. However, when fracture sets are closely spaced in a slope, a series or "family" of small wedges can be created. In this case, failure is usually a slower, gradual erosion of the slope surface. Nevertheless, both cases would be modeled using the same general geometry shown in Figures 3.1 and 3.2. In Figure 3.2, the general requirement is that the slope face dips more steeply than the line of intersection of the two major discontinuities (i.e., the line of intersection must "daylight" in the slope face). Likewise, the dip of the line of intersection must be greater than the rock's friction angle. In symbol form:

$$\psi_{fi} > \psi_i > \phi \quad (3.1)$$

where ψ_{fi} = dip of the slope face, ψ_i = plunge of the line of intersection and ϕ = friction angle.

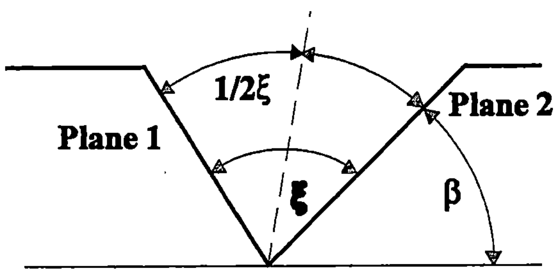

Figure 3.1 View of wedge geometry along the line of intersection.

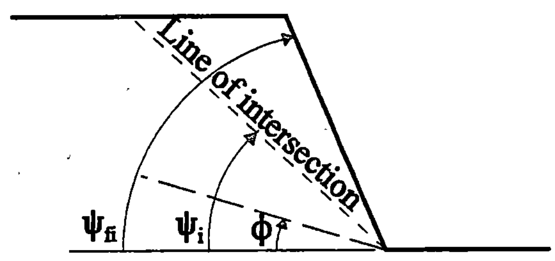

Figure 3.2 View of wedge geometry perpindicular to the line of intersection.

3.2.2 Analytical Assumptions

The following assumptions are made for the analysis of a wedge slide (due to Hoek & Bray, 1981):

- All forces are assumed to act through the centroid of the sliding mass. This implies that there are no moments created by the forces acting on the block. This assumption is not the case in most wedge slides, but the error introduced by ignoring the moments is negligible (Hoek & Bray, 1981).

- The shear strength of the sliding planes is defined by the Mohr-Coulomb criterion:

$$\tau = c + \sigma' \tan\phi \qquad \textbf{(3.2)}$$

where τ = shear stress, c = cohesion, σ' = effective normal stress, and ϕ = friction angle.

3.2.3 Water Force

The water force is calculated as the average pressure on each plane times the area of each plane. The formula used to calculate the average water pressure on each plane is taken from Hoek & Bray (1981). It is assumed that the distribution on each plane is tetrahedral. The formula for the average pressure on each plane is as follows:

$$u_1 = u_2 = \frac{1}{3} \times \left(\gamma_W \times \frac{H_W}{2}\right) = \frac{(\gamma_W \times H_W)}{6} \qquad \textbf{(3.3)}$$

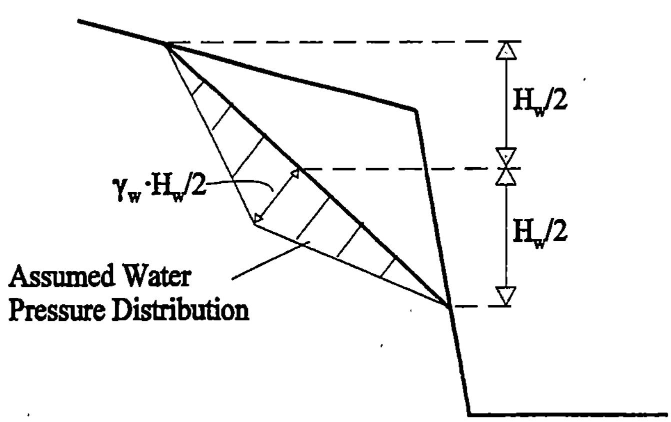

Figure 3.3 View perpendicular to the line of intersection showing the assumed water pressure distribution.

3.2.4 Rockbolts

There is debate over how rockbolts enhance the factor of safety of a rock slope. One viewpoint is that rockbolts add exclusively to the resisting force. Another possibility is that the components of the rockbolt force are split between the two, with the normal component adding to the resisting force and the shear component decreasing the driving force. Since it is impossible to determine the exact loading and movement sequence in a rock slope, the choice of which assumption to use becomes arbitrary (Hoek & Bray, 1981). *WedgeSlip* assumes that the normal component adds to the resisting force and the shear component decreases the driving force when calculating the factor of safety.

As in *PlaneSlip*, rockbolts are only drawn in the slope face. But rockbolts installed in the top face can be modeled (See *PlaneSlip* User's Guide for method) if care is taken to get the rockbolt angle, θ, correct. In the case of wedge failure, the plunge of the line of intersection takes the place of the sliding plane dip in plane failure when calculating the rockbolt angle.

3.2.5 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. Thus, one must define an index which describes the relationship between driving and resisting forces for each geometric and mechanical situation in a rock slope. This is traditionally done using an index called the *Factor of Safety,* defined as the ratio of the total resisting force to the total driving force. For wedge sliding, under gravity, the equation for calculating the Factor of Safety is as follows. See Table 3.1 for definition of variables.

$$FS = \frac{N_1^{'} \tan\phi + N_2^{'} \tan\phi + c_1 A_1 + c_2 A_2}{W \sin\psi_i} \quad \textbf{(3.4)}$$

If rock bolts are included the factor of safety equation is modified as follows. See Table 3.1 for definition of variables.

$$FS = \frac{[N_i^{'} + N_i^{'} + N_b\, F_b\, \mathrm{Cos}\beta]\, \mathrm{Tan}\phi + N_b S_b + (c_1 A_1 + c_2 A_2)}{W \mathrm{Sin}\psi_i - N_b F_b\, \mathrm{Sin}\beta} \quad \textbf{(3.5)}$$

Table 3.1 Definition of Variables

Variable	Description	Figure
N'_1, N'_2	Effective normal forces on planes 1 and 2; $N_i' = N_i - u_i A_i$	N/A
ϕ_1, ϕ_2	Friction angle of planes 1 and 2	Figure 3.2
c_1, c_2	Cohesive strengths of planes 1 and 2	N/A
A_1, A_2	Area of planes 1 and 2	N/A
W	Weight of the wedge	N/A
ψ_i	Plunge of the line of intersection of planes 1 and 2	N/A
u_1, u_2	Average water pressure on planes 1 and 2	Figure 3.3
N_b	Number of rockbolts	N/A
F_b	Tensile force in rockbolts	N/A
β	Angle rockbolts make with normal to the failure plane	N/A
S_b	Shear strength of rockbolts	N/A

3.3.1 Input Parameters

The following parameters can be edited by the user. A variables diagram (Figure 3.4) is presented to help visualize wedge geometry. A brief description, the units of measurement and range of values is given for each parameter in Table 3.2 below.

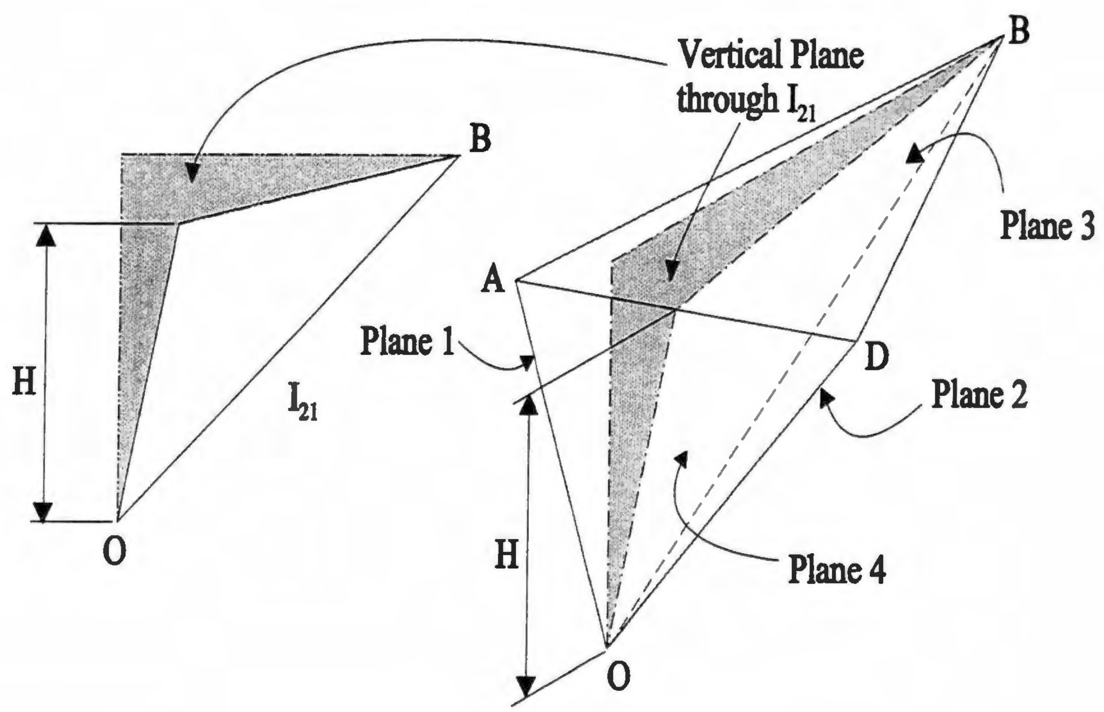

Figure 3.4 *WedgeSlip* Variables Diagram

Table 3.2 Input parameters for *WedgeSlip*.

Parameter	Description	Figure	Units of Measurement	Range
ψ1	Dip of sliding plane 1.	N/A	Degrees	0 to 180
α1	Dip direction of sliding plane 1.	N/A	Degrees	0 to 360
ψ2	Dip of sliding plane 2.	N/A	Degrees	0 to 180
α2	Dip direction of sliding plane 2.	N/A	Degrees	0 to 360
ψ3	Dip of top face.	N/A	Degrees	-90 to 90
α3	Dip direction of top face.	N/A	Degrees	0 to 360
ψ4	Dip of slope face.	ψ_{fi}, Figure 3.2	Degrees	0 to 90
α4	Dip direction of slope face.	N/A	Degrees	0 to 360
H	Height of slope face.	Figure 3.4	Meters or feet	1 to ∞
φ1 & φ2	Friction angle on sliding planes.	Figure 3.2	Degrees	0 to 89
c1 & c2	Cohesive strength on sliding planes.	N/A	kPa or psf	0 to ∞
u1 & u2	Mean pore pressure on sliding planes.	Figure 3.3	kPa or psf	0 to ∞
γ	Unit weight of the rock mass.	N/A	kN/m^3 or pcf	1 to ∞
N_b	Number of rock bolts.	N/A	N/A	0 to ∞
L_b	Length of rockbolts.	N/A	Meters or feet	0 to ∞
θ	Angle rockbolt makes with normal to the slope face.	N/A	Degrees	-90 to 90

Parameter	Description	Figure	Units of Measurement	Range
F_b	Axial capacity of rockbolts.	N/A	kN or kips	0 to ∞
ME	Required embedment length.	N/A	Meters or feet	1 to 30
S_b	Shear capacity of rockbolts.	N/A	kN or kips	0 to ∞

3.3.2 Display Options

The following options are located in the pull-down menu labeled "Upper Window" and "Lower Window" at the top of the program screen.

Enable Auto-Redraw Feature - This feature is on by default when the program is initially run. When this feature is enabled, the user can edit any of the parameters and see the immediate effects that they have on the cross section and/or factor of safety. Note that if this feature is not enabled then the *Redraw* and *Calculate* buttons must be used to recalculate the factor of safety and redraw the cross-section for each change in input.

Stereograph(UH) or Stereograph(LH) - This displays an upper or lower hemisphere stereographic projection of the current orientation data. Several options are available for display:

1. ***Plot Great Circles*** - Basic projection of each plane as a great circle on the stereonet (discontinuities are blue, slope and top faces are red, reference circle is dashed green).
2. ***Plot Dip Vectors*** - Plots the dip vectors for each plane (green).

3. ***Plot Normal Vectors*** - Plots the normal vectors for each plane (blue).

4. ***Highlight Removable Wedge*** (Available for LH projection only) - Highlights the removable wedge (yellow) as determined by block theory.

Cross Section - Displays a cross section of the current wedge in the corresponding window. The plane of the cross section is the vertical plane through the line of intersection of planes 1 & 2 (shaded in Figure 3.4).

Variables Diagram - Displays the variable diagram with plane numbering conventions and some dimensions of the wedge.

Save as Bitmap... - Allows the user to save the diagram that is currently displayed in either window as a bitmap. This command calls up a dialog box which allows the user to select a filename and directory to save the bitmap under.

Note that the user can also capture the currently active form and insert it into a document. Once the form you want to insert is on the screen and active, press Alt + Print Screen. This will capture the form. Then go to your document and select Paste to insert the image where you want it.

3.3.3 Command Buttons

These command buttons are located in the center of the program screen, just above the two output lines.

Redraw - If the *auto-redraw* function is not enabled, this button is used to command the program to redraw the cross-section using the current input.

Calculate - If the *auto-redraw* function is not enabled, this button is used to command the program to recalculate the factor of safety based on the current input.

3.3.4 Picture Controls

The following controls are located in the lower left-hand corner of each picture box.

Zoom In (+) - Allows the user to enlarge the size of the cross-section or stereograph in their respective picture box.

Zoom Out (-) - Allows the user to decrease the size of the cross-section or stereograph in their respective picture box.

Directional Buttons (horizontal and vertical scrollbars) - The directional buttons are used to move the cross-section or stereograph around within their respective picture box.

Reset Button (R)- The reset button returns the cross-section or stereograph to its original position in their respective picture box.

3.3.5 File Options

The following file options are located in the "File" pull-down menu.

Open - Allows the user to open and edit a file containing previously saved data.

Close - Closes the currently opened data file.

Save as - The user can save input data in a text file of their choice. These data files can then be recalled for use in calculations.

Print - Prints the current program display as seen on the screen.

Exit - Exits the program.

3.3.6 Data

These options can all be found under the "Data" pull-down menu.

Units of Measurement - *WedgeSlip* allows for the use of two different measuring systems, fps (English) and SI (Metric). When the units of measurement are changed at run-time, the program will convert each value to the appropriate unit system.

Show Additional Data - This option displays a text box directly below the factor of safety output line. The box contains useful data that is calculated by *WedgeSlip* such as plunge and trend of the line of intersection, area of each plane and volume of the wedge.

Typical Mechanical Parameters - *WedgeSlip* includes some common values for rock unit weight, discontinuity friction angle and rockbolt axial force in the "Data" pull-down menu.

Examples - There are also five example files that can be found under the "Data" pull-down menu. Example number one is from a limestone quarry, the second from a wedge slide along Interstate 40 in North Carolina, the third is the symmetric case discussed in Part 7, the fourth from a paper by B.K. Low and the last from TRB Special Report 247. Clicking on any of these examples automatically inserts the appropriate data and calculates the factor of safety.

3.3.7 Interpretation of Output

The main form of output in the *WedgeSlip* interface is the factor of safety and sliding mode displays, located just below the *Calculate* and *Redraw* buttons. The two picture boxes also serve as major sources of output because they can present an array of informative diagrams.

Factor of Safety - The common output of the program. Displays the calculated factor of safety for the current input if the auto-redraw function is enabled. If the auto-redraw function is disabled, displays the factor of safety for the data which was on the screen when the *Calculate* button was last selected.

Sliding Mode - Located directly above the factor of safety output line, the sliding mode output shows whether the sliding mode is double or single plane.

Additional Data - The user may wish to know the plunge and trend of the line of intersection or the true (dihedral) angle between the planes. This data is calculated by *WedgeSlip* and can be displayed by going to the pull-down menu labeled "Data" and clicking on the "Show Additional Data" command. The data is then displayed in a text box directly below the program output lines.

3.3.8 Worked Example

The example data is taken from field work done in a limestone quarry in Alabama. The site contains a multitude of slope configurations. The example presented here corresponds with the example used in *PlaneSlip*.

Step 1. Accessing Data - To access the example data (shown in Figure 3.5) go to the pull-down menu labeled "Data". Under that menu there will be a submenu entitled "Examples". Within that submenu there are several examples listed. Choose Example 1 (Limestone Quarry).

Step 2. Program Appearance - When the example first appears on the screen, the factor of safety should be equal to one and the sliding mode should be "Single Plane Sliding on Plane 1". The upper display should contain a cross-section of the wedge. The lower display should show a lower hemisphere stereographic projection of the planes in the slope. Note that the red circles represent the slope and top face, the blue circles represent the failure planes and the green circle is the reference circle. Figure 3.5 shows how your screen should look immediately after opening example 1. You may want to enlarge the cross-section or the stereographic projection at this point. Simply click on the "+" button located in the lower left corner of each picture box. The cross-section or stereographic projection should enlarge in regular increments each time the button is clicked.

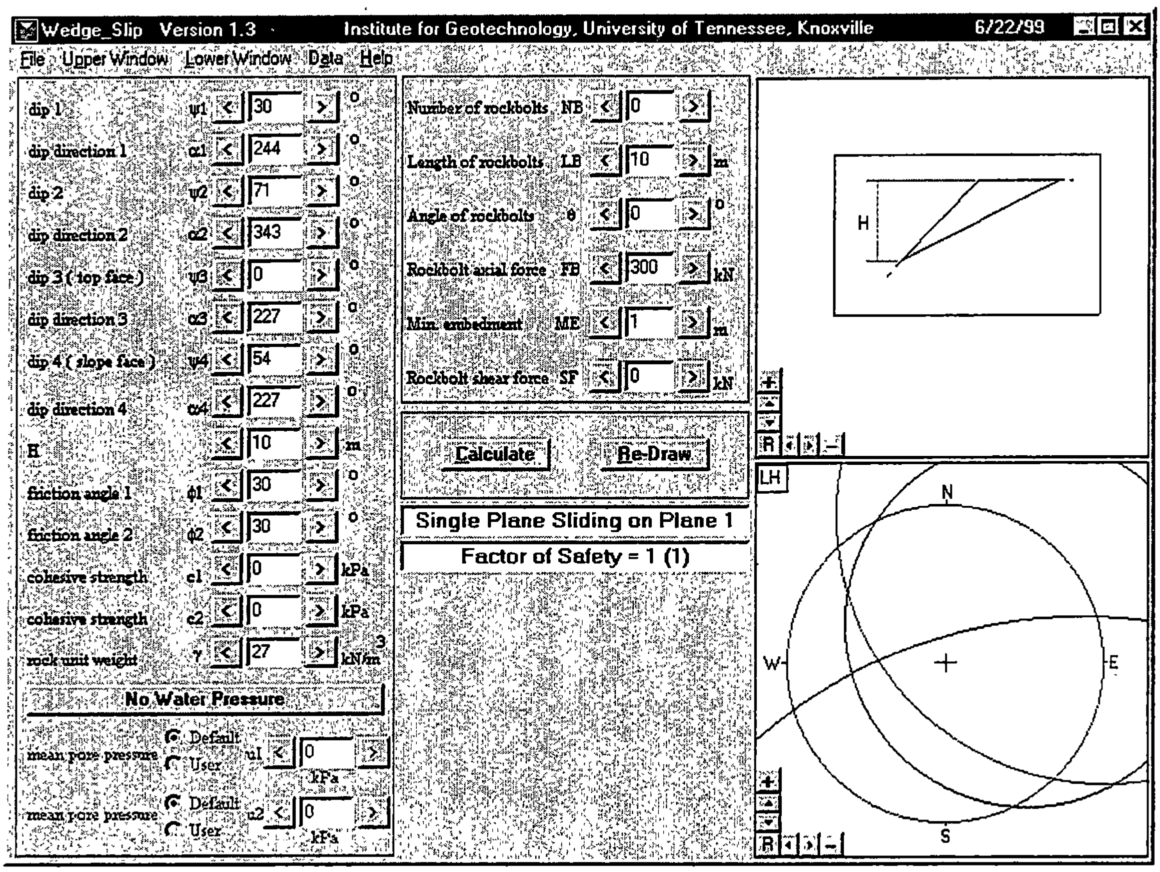

Figure 3.5 Example 1 output screen as it appears in *WedgeSlip*.

Step 3. Slope Geometry - Examine the effects that changing slope geometry have on the cross-section, and more importantly, on the factor of safety. For example, adjust the value for the face height, *h* (initially set to 10 meters), through a range of values and see how this affects the slope geometry and stability.

Step 4. Mechanical Parameters - Now change some of the mechanical parameters of the slope (i.e. friction angle, cohesion, unit weight). You should find that the slope's stability is least sensitive to unit weight and most sensitive to changes in the friction angle. Also note that since there is single plane sliding, only changes in mechanical parameters for plane 1 will result in a change in the factor of safety. Any change in plane 2 parameters should have no effect on the factor of safety. For example, decrease the friction angle on plane 1 from 30 to 20. The factor of safety should decrease from 1 to 0.63. Now decrease the friction angle on plane 2 by the same amount. There should be no change in the factor of safety.

Step 5. Water Pressure - Examine the effects of water pressure. As the average water pressure is increased, the factor of safety should decrease. If the water pressure on plane 1 is raised to 40 kPa, a message should inform you that "Normal forces are negative on planes 1 & 2". This means the slope is highly unstable for this scenario.

Step 6. Rockbolts - Now add reinforcement to the slope. Note any bolts that appear as a dashed line. This means they are not long enough to meet the minimum embedment requirement and are not included in the stability calculations. Try varying the axial and shear force and orientation of the rockbolts. As the strength of the bolts is increased, so should the factor of safety.

Step 7. Additional Data - The user may wish to know the plunge and trend of the line of intersection or the true (dihedral) angle between the planes. This data is calculated by *WedgeSlip* and can be displayed by going to the pull-down menu labeled "Data" and clicking on the "Show Additional Data" command. The data is then displayed in a text box directly below the program output lines.

3.3.9 Troubleshooting

The factor of safety and sliding mode displays have several comments that are shown when certain conditions exist in the data. The following is a summary of those possible outputs with a brief explanation of the cause of each output.

Wrong Data Entry - This error message can be caused by a variety of factors. However, it is usually a result of erroneous wedge geometry which causes a division by zero in the program calculations. It can also denote that the calculated line of intersection plunges back into the slope. Make sure that no input values have transposed numbers. If there is no obvious error, a hand analysis of the wedge in question may be required to determine the problem.

Driving Force is Upward or Equal to Zero - Occurs when the calculated driving force is equal to or less than zero. This creates a problem since the factor of safety equation will result in a division by zero. Usually, this is a result of erroneous slope geometry.

Normal Forces are Negative on Planes 1 & 2 - Both planes have normal forces less than or equal to zero acting on them. This can be caused by infeasible wedge geometries, but in most cases is a result of excessive water pressure on both planes.

Sliding Line is Horizontal - The line of intersection is horizontal and does not require analysis. This is a result of the wedge geometry. Note that water pressure could create an instability in this situation. However, *WedgeSlip* assumes that this is an unlikely occurrence and reports that the sliding line is horizontal.

No Wedge Formed - This error occurs when there is an infeasible wedge geometry entered. It can mean that the line of intersection plunges back into the slope (among other things). As mentioned before, if there is no obvious error in the data input then hand calculations are recommended to decipher the problem.

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PART IV

ROCKSLIP

VERSION 1.3

USER'S GUIDE

A computer program for the stability analysis of slopes in cylindrically folded rocks.

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LIST OF FIGURES

CHAPTER 4.1 INTRODUCTION

4.1.1 Program Development

RockSlip Version 1.3 was developed by The Institute for Geotechnology, Department of Civil Engineering, The University of Tennessee at Knoxville as part of a research project for the Tennessee Department of Transportation. The program authors are Dr. Matthew Mauldon, Scott Arwood, You Li, Yen-Yit Chan and Joshua Cole. Any questions or comments about *RockSlip* should be addressed to:

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http://www.engr.utk.edu/research/geo/institute

4.1.2 Disclaimer

The authors disclaim any responsibility for the correctness of the data generated by the *RockSlip* package, or for the consequences resulting from the use thereof. Any use or misuse of this package is the sole responsibility of the user.

4.1.3 Program Features

The following guide has been developed to help users understand and operate the *RockSlip* program. The *RockSlip* program was developed by modeling a rock wedge with multiple sliding surfaces as a prismatic block. A new analytical model for determining slope stability in this situation has been described by Mauldon and Ureta (1996) and Mauldon, Arwood and Pionke (1998). The model is based on determining the distribution of normal forces on the failure surfaces by minimizing the potential energy of the system. The theory will not be presented in detail here. For a detailed discussion please see Mauldon, Arwood and Pionke (1998). Program features include:

- **Water Level** - The height of water in the tension crack controls the magnitude of water pressure acting on the slope.
- **Drainage Impedance** - A parameter entitled "drainage impedance" has been incorporated into the program, which allows the user to change the pressure distribution behind the slope by varying the drainage conditions along the sliding planes and at the toe of the slope.
- **Units of Measurement** - *RockSlip* allows for the use of two different measuring systems, fps (English) and SI (Metric).
- **Y2K Compliant** - *RockSlip* includes no references to date and is therefore fully Y2K compliant.

4.1.4 Program Installation

RockSlip is compatible with *Windows 95/98/NT*. Approximately 4MB of free hard drive space is required to install the program. There should be two 3 ½ " floppy disks included for the setup of *RockSlip*. Insert the disk labeled "Setup Disk 1 of 2" into your floppy disk drive (usually labeled drive a: or b:). Click on the **Start** button, go to **Run** and type in "a:\setup.exe" (or "b:\setup" depending on your drive letter). Then follow the instructions that appear on your screen to setup *RockSlip*.

If you have the "Sample Bitmaps" disk, and wish to access them in *RockSlip*, create a new folder entitled "Images" under the directory "C:\Program Files\Rs". This is the folder that *RockSlip* will look in when you tell it to open a bitmap. Once you create the new folder simply copy the files on the "Sample Bitmaps" disk to the new folder. This will complete the installation process for *RockSlip*.

CHAPTER 4.2 THEORY

4.2.1 Slope Geometry

Certain geologic environments produce blocks which cannot be modeled accurately as wedge or plane slides and cannot be evaluated with limiting equilibrium methods. An example is a block formed by cylindrically folded sedimentary rocks. For this case, the sediments were initially deposited in horizontal bedding layers. In the millions of years since, the rocks have been compressed horizontally by tectonic movement. This compression folded the depositional layers into ridges and valleys. As shown in Figure 4.1, the folds form synclines and anticlines, with synclines being concave upward and the anticlines concave downward. If the layers are folded and tilted, but not twisted, the normals to the bedding surfaces will remain coplanar and the folding is termed cylindrical (Ramsay and Huber, 1987). When these rocks are folded the interlayer contacts are weakened, analogous to bending a deck of cards, and interlayer slip may occur. When slopes are cut through these folded rocks, failures may occur along the contacts of these bedding layers. The sliding surface in such cases cannot be described as single plane or an intersection of two planes, but is a curved surface as in Figure 4.2. Studies have shown that if these blocks are idealized as a two plane wedge, as is commonly done in practice, the factor of safety may be overestimated (Mauldon, Arwood and Pionke, 1998). A cylindrical block could be idealized as a prismatic block with multiple sliding planes, all with parallel lines of intersection, as shown Figure 4.3. The model for the stability of these prismatic blocks will be presented first and then extended to where the number of planes m approaches infinity. A local coordinate system, which will later be used in the model development, is also defined in Figures 4.2 and 4.3 with the Z axis parallel to the fold axis and X and Y in the plane orthogonal to the fold axis.

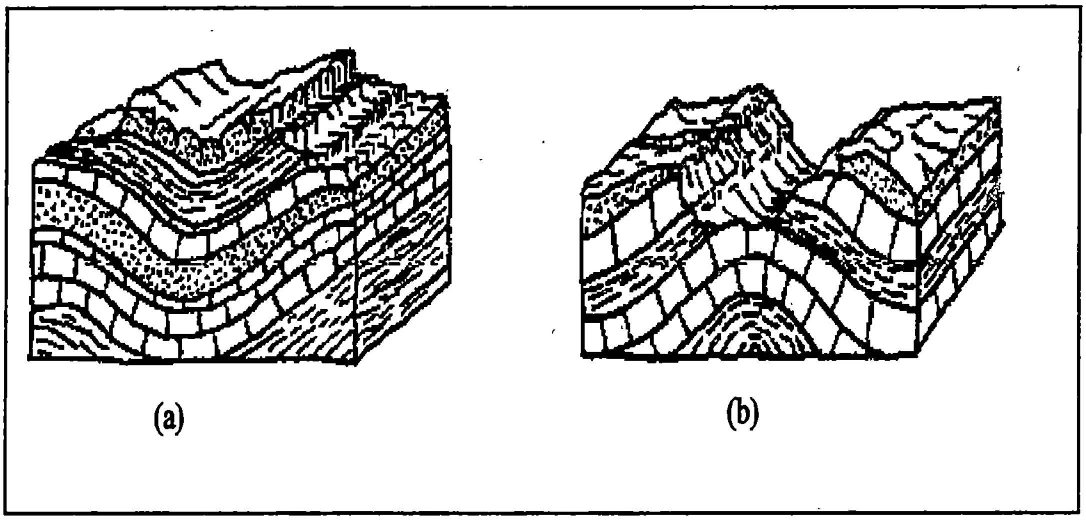


Figure 4.1 Two fold structures (a) a syncline, and (b) an anticline (Wilson, 1981).

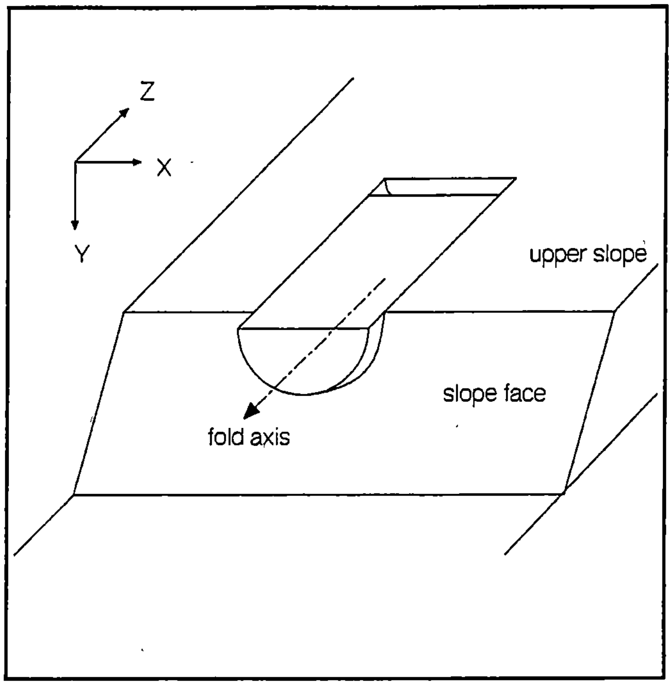


Figure 4.2 Cylindrical block formed in folded rocks.

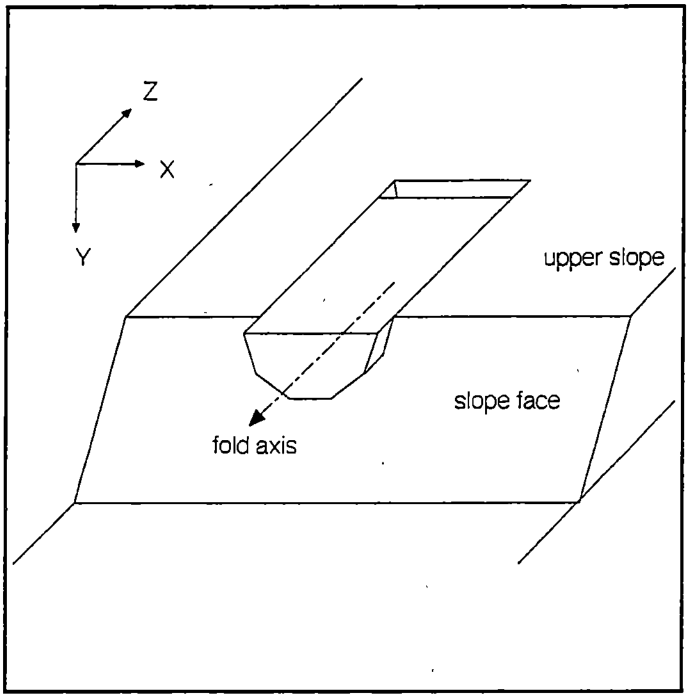


Figure 4.3 Cylindrical block idealized as a prismatic block.

4.2.2 Analytical Assumptions

The following assumptions are made when the potential energy model is implemented in *RockSlip*:

- Each contact face of the rock block, *n*, is assumed to have a normal stiffness of k_n, whereas the previously published work employed a uniform spring stiffness constant for all contact surfaces.
- The block itself is assumed to be undeformable, deformation occurring only at the contact faces.
- The block is acted upon by an active resultant force ***R***, which includes self weight, and may include other forces such as water pressure and cohesion.
- An important assumption is that the frictional shear stresses act parallel to the direction of sliding only (Hoek and Bray, 1981; Chan and Einstein, 1981). This is a standard assumption in limiting equilibrium analyses.
- An elastic, conservative system is assumed to determine the distribution of normal forces that minimizes the potential energy of the system. Knowledge of these normal forces will then allow the stability to be determined.
- The coordinate system is the same as that defined in Figure 4.3.
- Each plane has a length L_n in the XY plane, and since this is a prismatic block, the other dimension of the contact plane will be taken as a unit length in the Z (fold axis) direction.

4.2.3 Water Force

A detailed explanation of the water force calculation can be found in Part 8 of this document. The same basic principles used in *WedgeSlip* are utilized in the *RockSlip* calculations. The major difference is that the volume calculation in *RockSlip* is much more complicated and is obtained by Gaussian Numerical Integration. The parameter z, height of water level in tension crack, and drainage impedance are included in the "Outcrop" form and can be modified according to the water level and drainage conditions of the slope.

4.2.4 Potential Energy Minimization

RockSlip deals with failures involving multiple or curved sliding surfaces. The analysis procedure, which was originally developed for stability analysis in folded rocks, is based on minimization of potential energy. For a detailed explanation of the potential energy minimization method please refer to Mauldon and Ureta (1996) and Mauldon, Arwood and Pionke (1998). Due to the lengthy mathematical formulations involved, an explanation of the method will not be presented here.

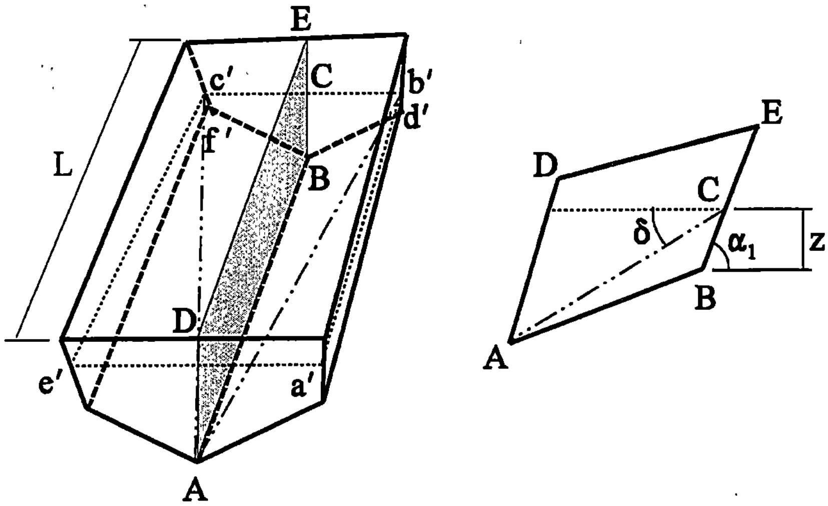
CHAPTER 4.3 USING *RockSlip*

4.3.1 Saving Bitmaps

The first step to operating *RockSlip* is to open a bitmap or points file. It is important that the user store his/her bitmaps under a directory that can easily be found (*RockSlip* defaults to the directory "C:/Program Files/Rs/Images" when opening a bitmap). The size at which bitmaps are saved determines whether the user will be able to view the slope picture in its entirety. For the entire bitmap image to fit into the "Profile" form it needs to be 360 x 235 pixels. The easiest way to accomplish this task is to resize the image with an image editor (L View, Adobe Photoshop, Corel Photo House). Be careful to preserve the aspect ratio when resizing the bitmap, otherwise, your image may be distorted which may affect the computed factor of safety. Once the size of the bitmap is correct, one can open it and begin to define the failure planes to be analyzed.

4.3.2 Defining Planes

The following method will focus on using a bitmap to define the sliding planes. To open a bitmap, click on the File pull-down menu. There should be two submenus entitled "Open Bitmap" and "Open Points". Clicking on the "Open Bitmap" submenu causes an "Open File" dialog box to be displayed. The user can browse through the directories and find the appropriate bitmap. After the bitmap is open and showing in the "Profile" form, the user can move the mouse around to define the coordinates of the planes. Click once on the picture to define the beginning of a line and move the mouse to the desired endpoint and click again. Make sure that the plane coordinates are defined from right to left. In this manner, all the sliding planes can be defined in terms of coordinates on the Visual Basic axes. The next step is to enter in the input parameters from the outcrop data. To accomplish this, click on the Next button to bring up the "Outcrop" form.



(a)

(b) Vertical section through line AB.

Figure 4.4 *RockSlip* Variables Diagram

4.3.3 Input Parameters

Input parameters, which are displayed next in the "Outcrop" form, can be edited by the user. A brief description, the units of measurement and range of values is given for each parameter in Table 4.1.

4.3.4 Picture Controls

Once the outcrop information has been entered, click on the Next button and the "Calculate" form will appear. There are two diagrams displayed along with the Factor of Safety and other results on this form. One is the **apparent section**. The apparent section is how the defined planes appear as they are drawn on the bitmap. The **true section** corrects the previous picture based on the orientation of the fold axis with respect to the outcrop face orientation. The user also has four zoom options (25%, 50%, 100% and 200%) located to the right of the two diagrams.

Table 4.1 Definition of Input Parameters for *RockSlip.*

Parameter	Description	Figure	Units of Measurement	Range
Fold Axis Trend	Trend of fold axis.	Fig 4.2 & 4.3	Degrees	0 to 360
Fold Axis Plunge	Plunge of fold axis.	Fig 4.2 & 4.3	Degrees	0 to 90
Outcrop Dip	Dip of outcrop face.	N/A	Degrees	0 to 90
Outcrop Dip Direction	Dip direction of outcrop face.	N/A	Degrees	0 to 360
Friction Angle	Friction angle of sliding planes.	N/A	Degrees	0 to ∞
Water Level	Water level (vertical height) in tension crack.	z, Fig 4.4	Meters or feet	0 to ∞
Drainage Impedance	Parameter which describes drainage conditions at the toe of the slope. 0% = fully drained toe, 100% = no drainage at toe.	N/A	%	0 to 100
Upper Slope Length	Length of upper slope.	L, Fig 4.4	Meters or feet	0 to ∞
Cohesion	Cohesion of sliding planes.	N/A	kPa or psf	0 to ∞
Unit Weight	Unit weight of the rock mass.	N/A	kN/m^3 or pcf	0 to ∞

4.3.5 Interpretation of Output

The main form of output in the *RockSlip* interface is the "calculate" form. The output box located on this form displays several paragraphs of output including the factor of safety, outcrop data, number and length of planes and other data. The two picture boxes also serve as sources of output because they show how the wedge looks in apparent and true cross-section. Clicking on the "Finish" button exits the analysis.

4.3.6 Worked Example

The following example is based on data gathered from a field site in Biltmore, TN (Arwood, 1996). The outcrop information is already entered in the program as the default settings. Depending on the number of planes defined, a variety of different factors of safety are obtained.

Step 1. Accessing Bitmaps - To access the example bitmap, go to the pull-down menu "File" and select "Open Bitmap". A dialogue box should open to the directory where the sample bitmaps (included with program) are located. Choose "Bilt1A.bmp" and press open. (See Figure 4.5).

Step 2. Defining Failure Planes - Once the Biltmore bitmap has been chosen, one can now define the failure planes to be analyzed. Begin by examining a wedge configuration (See Figure 4.6), i.e. define two planes. After the two planes have been defined, click the next button.

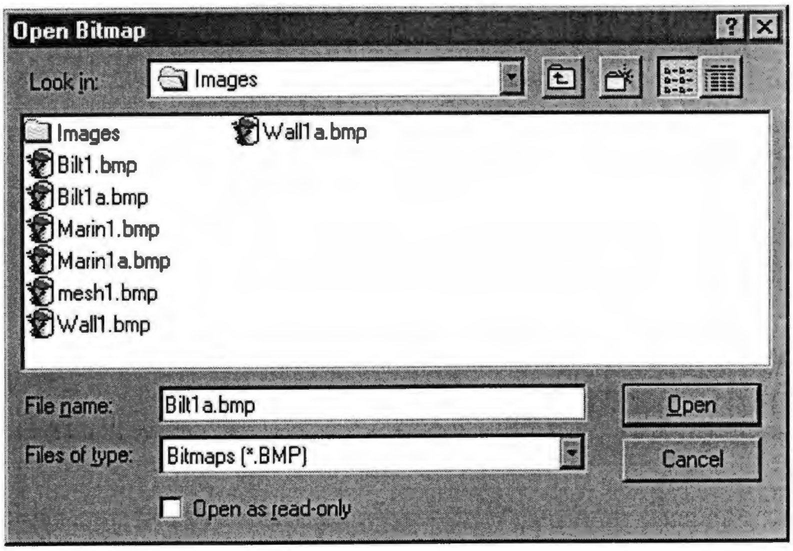


Figure 4.5 Opening a Bitmap in *RockSlip*.

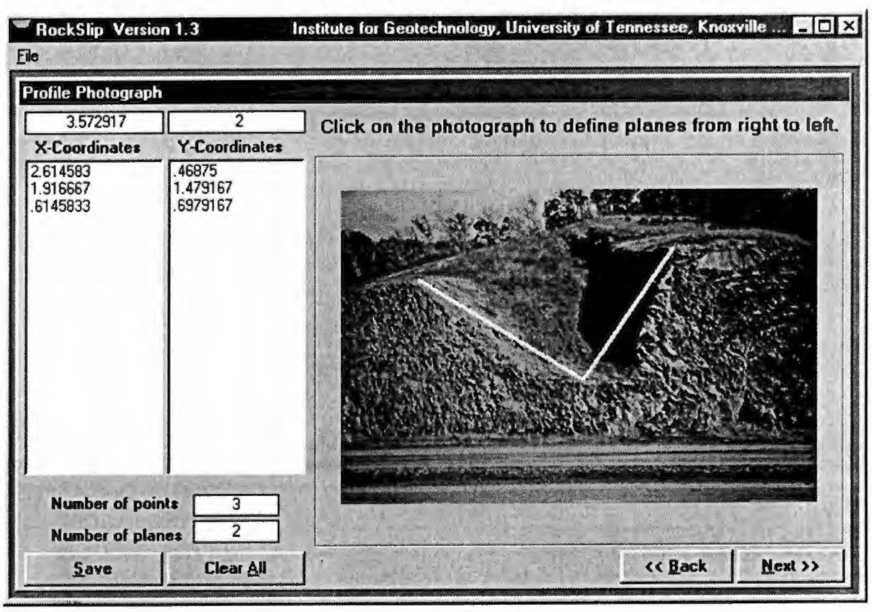


Figure 4.6 Defining Planes (Wedge Configuration)

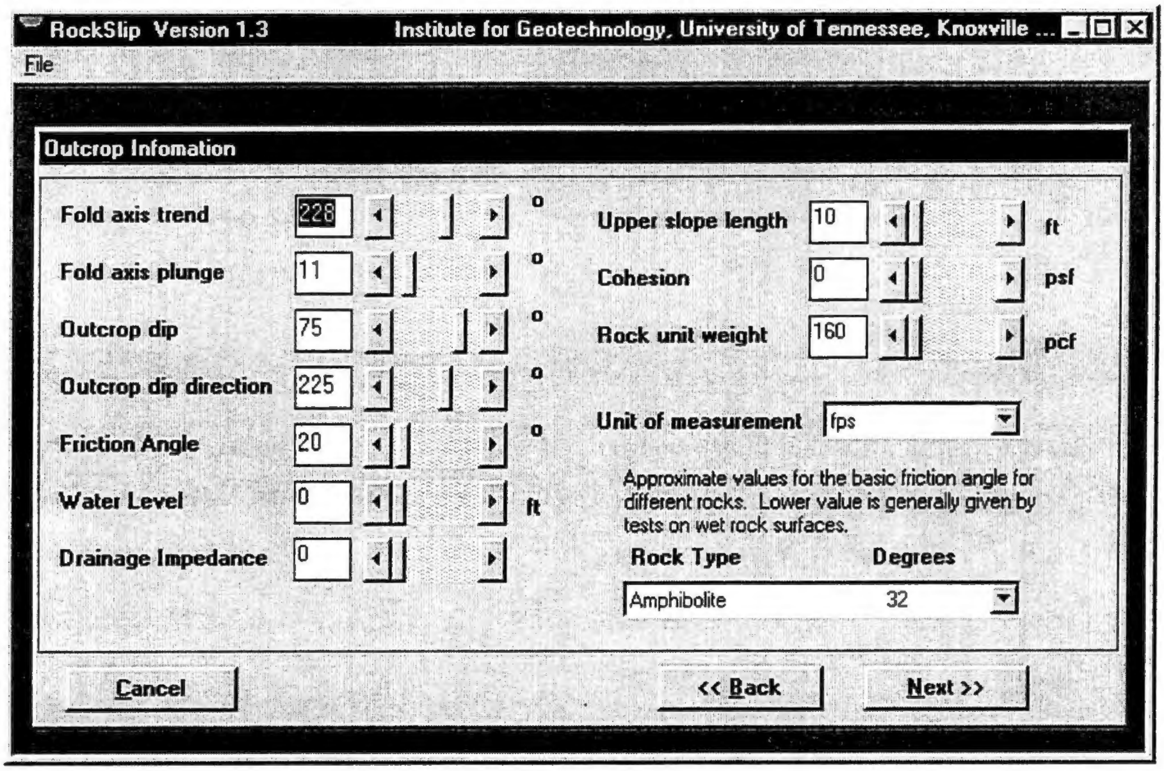


Figure 4.7 "Outcrop" form with default data.

Step 3. Program Appearance - The "Outcrop" form should appear as in Figure 4.7, with the same default data. This data corresponds to the field data gathered from the Biltmore site. Click on the next button.

Step 4. Results - *RockSlip* now displays the "Calculate" form. All the outcrop information is summarized in this form (See Figure 4.8). The factor of safety is also reported. The factor of safety should be in the range of 2.3 to 2.5 depending on how you defined your planes.

Step 5. Outcrop Data - Click the back button to go to the "Outcrop" form. At this point, one can adjust the outcrop data (i.e. fold axis and outcrop orientation, mechanical

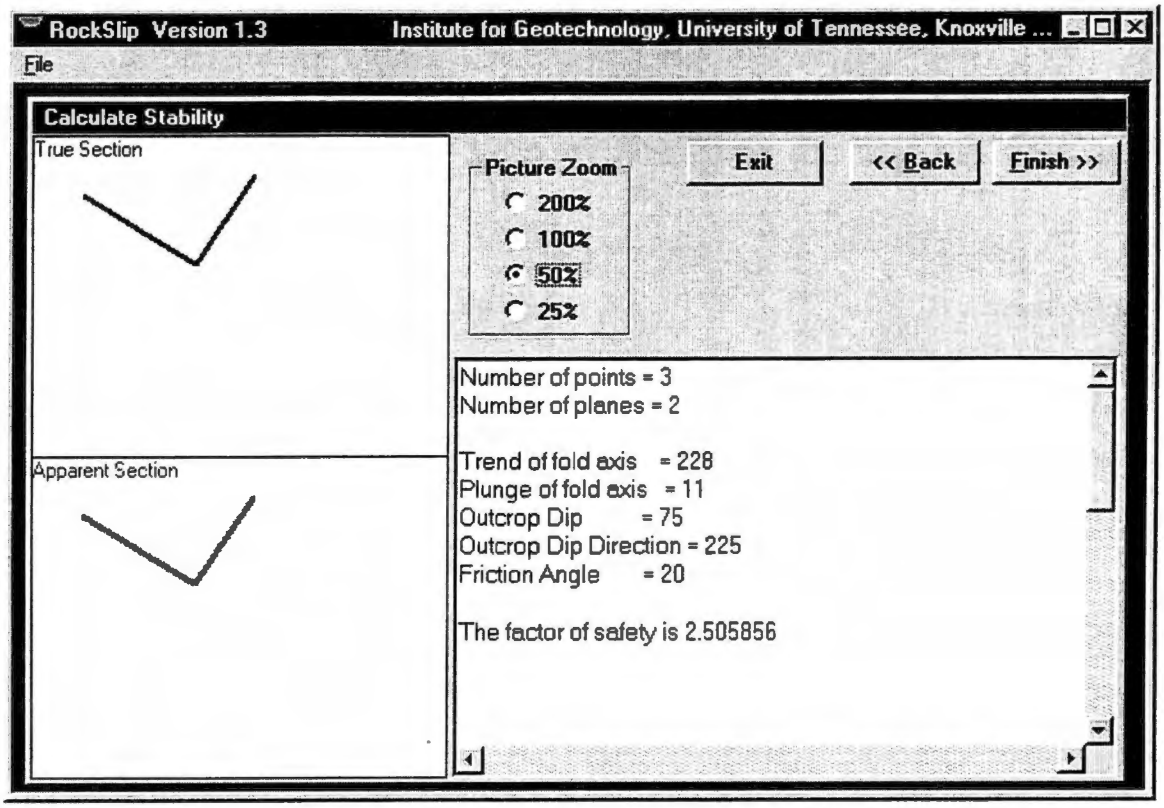


Figure 4.8 "Calculate" form as it appears in *RockSlip*

parameters, etc.) and see how it affects the factor of safety. For instance, if you decrease the friction angle from 20 to 10 and click the next button the factor of safety should drop considerably (for a trial run, the FS dropped from 2.48 to 1.19 when the friction angle was lowered from 20 to 10). Try changing all of the parameters and observe the effects they have on the factor of safety. One important thing to notice is how *RockSlip* handles the true" versus "apparent" section diagrams. Try adjusting the dip direction of the slope face or the fold axis trend to values which are significantly different. Then click next. The apparent section should be quite different from the true section. As the two values get closer to each other, however, the true and apparent sections should come closer to agreeing with one another.

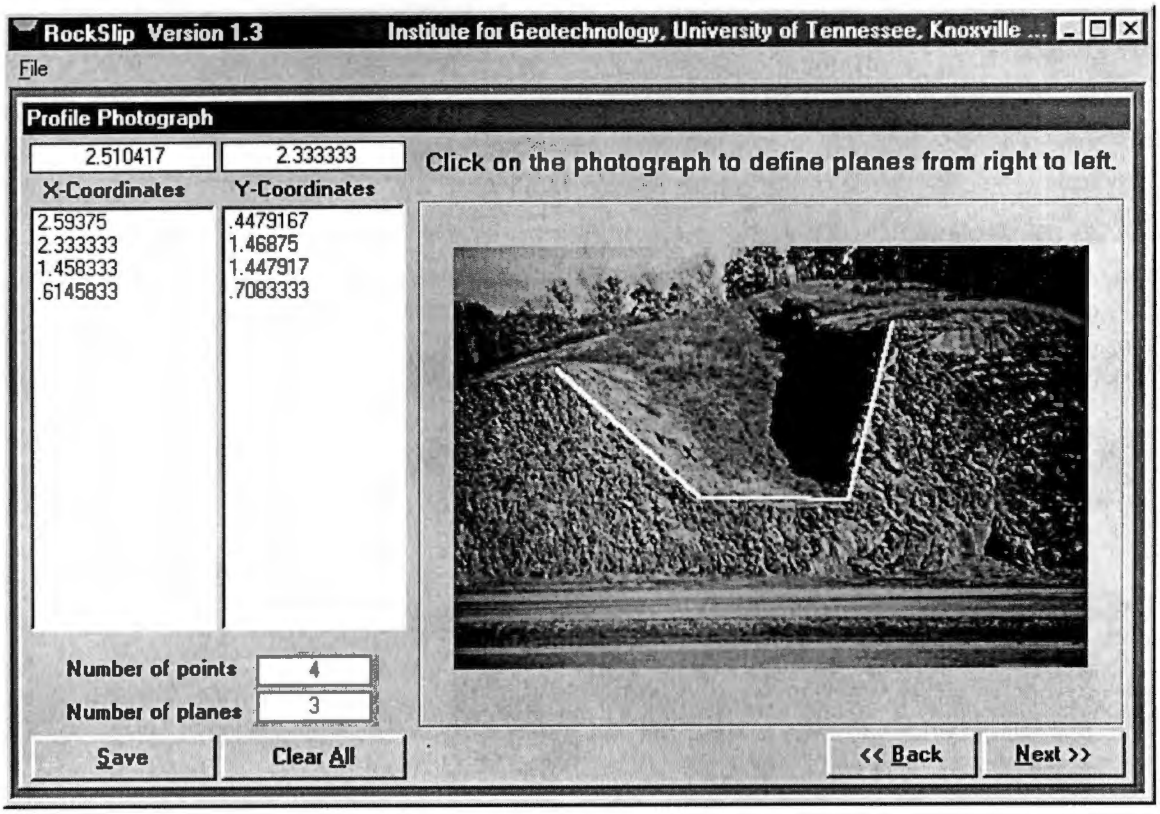


Figure 4.9 Three sided failure surface in *RockSlip*.

Step 6. 3-sided and 5-sided Failure Surfaces - Now examine two more plane configurations, the 3-sided and 5-sided failure surfaces. Click the back button until you arrive at the "Profile" form. Click the clear all button to erase the previous plane definitions. Now define 3 planes along the failure surface (See Figure 4.9) and repeat steps 3 through 5. The factor of safety should be in the range of 1.3 to 1.5. Repeat the process and define 5 planes for the next analysis (See Figure 4.10). The factor of safety in this case should be between 1.0 and 1.4.

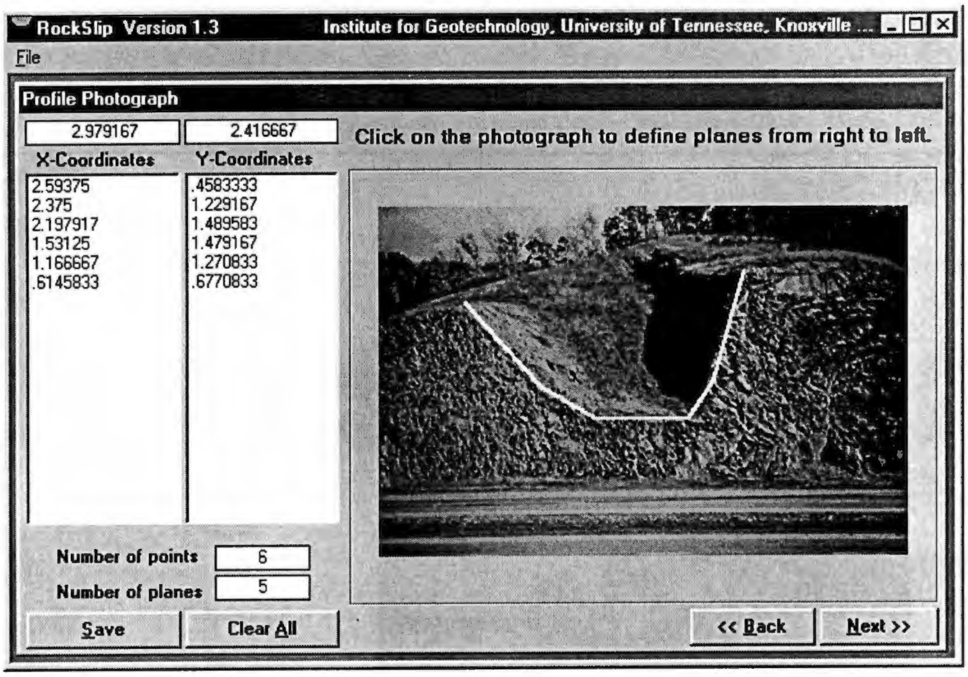


Figure 4.10 Five sided failure surface in *RockSlip*.

4.3.7 Troubleshooting

If there is an error in the calculations a message box will appear before the results form appears. The following is a summary of the possible outputs that can appear in the message box.

Driving Force is Upward or 0! **-** The driving force acting on the block is less than or equal to zero. This means that for the particular geometry and input values the block is stable.

Normal Force is Negative **-** The normal force acting on each plane is less than or equal to zero. This causes the frictional resistance on each plane to be zero also. This denotes a highly unstable block. This problem is likely caused by excessive water force acting on the sliding planes.

References

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Chan, H.C. and Einstein, H.H. (1981). "Approach to Complete Limit Equilibrium Analysis for Rock Wedges - The Method of Artificial Supports." *Rock Mechanics*. 14, 59-86.

Hoek, E. and Bray, J. (1981). *Rock Slope Engineering*. Institute of Mining and Metallurgy, London.

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Mauldon, M., Cole, J.H. (1998). *Slope Stability in Folded Rocks*, Tennessee Department of Transportation Final Report, Dept. of Civil & Environmental Engineering, University of Tennessee, Knoxville.

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Ramsay, J.G. and Huber, M.I. (1987). *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures*. Academic Press Limited, San Diego.

Ureta, J.A. (1994). "Stability Analysis of Prismatic Rock Blocks." Master's Thesis, Dept. of Civil & Environmental Engineering, University of Tennessee, Knoxville.

PART V

VERIFICATION AND EXAMPLES

List of Figures

VERIFICATION AND EXAMPLES

This chapter presents some simple examples which can be checked analytically. Comparisons between the results from the computer program and the analytical results are presented in Tables 5.1, 5.2 and 5.4. Also presented are comparisons with published results (Table 5.3).

5.1 *PlaneSlip*

5.1.1 Plane Example (No Tension Crack)

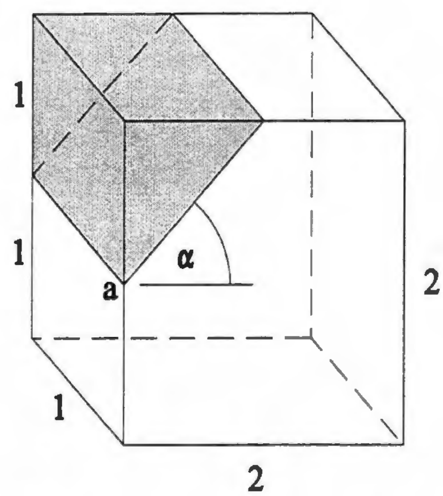


Figure 5.1 Plane example (no tension crack)

This example uses a simple slope geometry (Figure 5.1) to verify *PlaneSlip*. The point *a* is fixed at the midpoint of the side of the cube. The angle α is variable in the range (26.57°, 90°), thus a variety of plane geometries are possible depending on its value. A unit length of 1 in the perpendicular direction is assumed. To calculate the Factor of Safety against plane sliding, the following steps are taken:

Step 1. Calculate the volume of the prism of rock

Volume = ½ × base × height × length of prism = ½ × 1 × cot α = cot α / 2

Step 2. Calculate the weight of the prism

Weight = W = Volume × Unit Weight = cot $\alpha \times \gamma$ / 2

Step 3. Calculate the driving force

$F_D = W \sin\alpha - NT \sin\beta$

Step 4. Calculate the resisting force (without water pressure)

$F_R = (W \cos\alpha + NT \cos\beta) \times \tan\phi + (c / \sin\alpha) + NS$

where N = number of rockbolts embedded a length greater than the minimum embedment length, T = tensile force in rockbolts, β = the angle the bolt or cable makes with the normal to the failure plane, c = cohesion, ϕ = friction angle, S = shear force (dowel effect) produced by a single rockbolt and 1 / sin α is the length of the slide plane for the no tension crack case.

Step 5. Calculate the factor of safety

$FS = F_R / F_D = [(W \cos\alpha + NT \cos\beta) \times \tan\phi + (c / \sin\alpha) + NS] / W \sin\alpha - NT \sin\beta$

5.1.2 Plane Example (With Tension Crack)

Now add a tension crack (fixed as a vertical plane through the middle of the cube) and introduce water pressure. This sets the face height and the length equal to 1 (Figure 5.2). Note that the length of the sliding plane is calculated differently than the no tension crack case. Water pressure decreases the resisting forces and increases the driving forces.

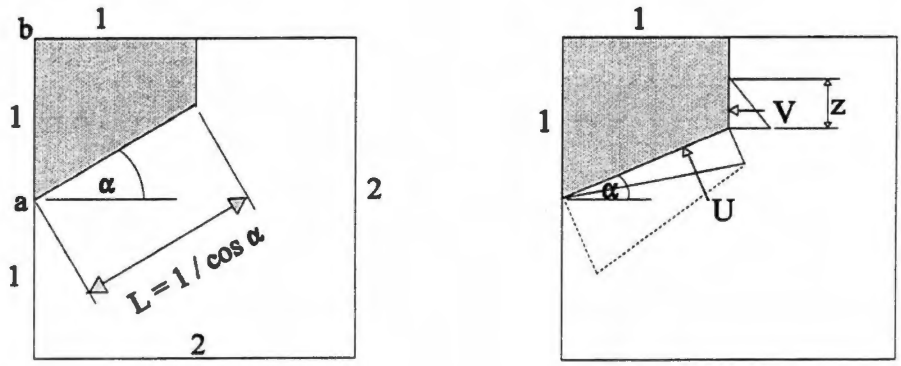


Figure 5.2 Plane example (with tension crack)

Figure 5.2 is a diagram illustrating the assumed pressure distributions for this model. If there is drainage impedance at the toe of the slope then the distribution will be modified accordingly (denoted by the dotted line). Rockbolts and cohesion are omitted from these calculations.

Step 1. Calculate the volume of the prism of rock

Volume = $(1 \times 1 - \frac{1}{2} (\tan\alpha \times 1)) \times 1 = 1 - \tan \alpha / 2$

Step 2. Calculate the weight of rock

Weight = $(1 - \tan \alpha / 2) \times \gamma$

Step 3. Calculate the water force, V, on the tension crack (fully drained toe)

$V = \frac{1}{2} \times \gamma_w \times z^2$

Step 4. Calculate the water force, U_D, on the sliding plane

$U_D = \frac{1}{2} \times \gamma_w \times z (1 / \cos \alpha)$

Step 5. Calculate the effective stress, N', acting on the slide plane

$N' = W \cos \alpha - V \sin \alpha - U_D$

Step 6. Calculate the factor of safety for a fully drained toe

$FS = N' \tan \phi / (W \sin \alpha + V \cos \alpha)$

Step 7a. Calculate the added water force, U', on the sliding plane when drainage at the toe is completely impeded

$U' = ½ (\tan \alpha + z)\gamma_w(1 / \cos \alpha)$

Thus, the total water force, U_U, on the sliding plane for a fully impeded toe (undrained case) is:

$U_U = U_D + U'$

Step 7b. If the toe is not fully impeded, then the added water force, U', is modified by the amount of drainage impedance, ξ. The equation becomes:

$U_I = U_D + (\xi \times U')$

Step 7c. If there is negative drainage impedance, ξ, then U_D is calculated with a different equation:

$U_D = ½ \times \gamma_w \times z \times [(1 + \xi) \times (1 / \cos \alpha)]$

In either case, the correct value for U should be substituted into the factor of safety equation to obtain the correct factor of safety.

5.1.3 Verification

These examples were entered in *PlaneSlip* and the factor of safety acquired for each case. These results were compared with spreadsheet calculations based on the previous formulas. Four examples for each variable were run, with all other variables being held constant, and results obtained. The following spreadsheet (Table 5.1) shows the results from both cases (with and without tension crack) and compares them with results from *PlaneSlip*, thus verifying the accuracy of *PlaneSlip* for these simple cases.

Table 5.1 *PlaneSlip* verification exercise (see Table 2.2 for definition of variables).

PlaneSlip Verification Exercise																		
6/24/99																		
α	γ	φ	c	N	T	S	β	z	ξ	Vol	Wt.	V	Ud	U'	Fr	Fd	FS	FS (*PS*)
20	25	30	0	0	1	1	10	0	0	1.4	34.3	0.00	0.00	0.00	18.6	11.7	**1.59**	**1.59**
40	25	30	0	0	1	1	10	0	0	0.6	14.9	0.00	0.00	0.00	6.6	9.6	**0.69**	**0.69**
60	25	30	0	0	1	1	10	0	0	0.3	7.2	0.00	0.00	0.00	2.1	6.3	**0.33**	**0.33**
80	25	30	0	0	1	1	10	0	0	0.1	2.2	0.00	0.00	0.00	0.2	2.2	**0.10**	**0.10**
30	**26**	30	0	0	1	1	10	0	0	0.9	22.5	0.00	0.00	0.00	11.3	11.3	**1.00**	**1.00**
30	**27**	30	0	0	1	1	10	0	0	0.9	23.4	0.00	0.00	0.00	11.7	11.7	**1.00**	**1.00**
30	**28**	30	0	0	1	1	10	0	0	0.9	24.2	0.00	0.00	0.00	12.1	12.1	**1.00**	**1.00**
30	**29**	30	0	0	1	1	10	0	0	0.9	25.1	0.00	0.00	0.00	12.6	12.6	**1.00**	**1.00**
30	25	**10**	0	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	3.3	10.8	**0.31**	**0.31**
30	25	**20**	0	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	6.8	10.8	**0.63**	**0.63**
30	25	**30**	0	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	10.8	10.8	**1.00**	**1.00**
30	25	**40**	0	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	15.7	10.8	**1.45**	**1.45**
30	25	30	**5**	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	20.8	10.8	**1.92**	**1.92**
30	25	30	**10**	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	30.8	10.8	**2.85**	**2.85**
30	25	30	**15**	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	40.8	10.8	**3.77**	**3.77**
30	25	30	**20**	0	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	50.8	10.8	**4.70**	**4.69**
30	25	30	0	**2**	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	14.0	10.5	**1.33**	**1.33**
30	25	30	0	**4**	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	17.1	10.1	**1.69**	**1.69**
30	25	30	0	**6**	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	20.2	9.8	**2.07**	**2.07**
30	25	30	0	**8**	1	1	10	0	0	0.9	21.7	0.00	0.00	0.00	23.4	9.4	**2.48**	**2.48**
30	25	30	0	1	**5**	1	10	0	0	0.9	21.7	0.00	0.00	0.00	14.7	10.0	**1.47**	**1.47**
30	25	30	0	1	**10**	1	10	0	0	0.9	21.7	0.00	0.00	0.00	17.5	9.1	**1.93**	**1.93**
30	25	30	0	1	**15**	1	10	0	0	0.9	21.7	0.00	0.00	0.00	20.4	8.2	**2.48**	**2.48**
30	25	30	0	1	**20**	1	10	0	0	0.9	21.7	0.00	0.00	0.00	23.2	7.4	**3.16**	**3.16**
30	25	30	0	1	1	**5**	10	0	0	0.9	21.7	0.00	0.00	0.00	16.4	10.7	**1.54**	**1.54**
30	25	30	0	1	1	**10**	10	0	0	0.9	21.7	0.00	0.00	0.00	21.4	10.7	**2.01**	**2.01**
30	25	30	0	1	1	**15**	10	0	0	0.9	21.7	0.00	0.00	0.00	26.4	10.7	**2.48**	**2.48**
30	25	30	0	1	1	**20**	10	0	0	0.9	21.7	0.00	0.00	0.00	31.4	10.7	**2.95**	**2.95**
30	25	30	0	1	1	1	**20**	0	0	0.9	21.7	0.00	0.00	0.00	12.4	10.5	**1.18**	**1.18**
30	25	30	0	1	1	1	**40**	0	0	0.9	21.7	0.00	0.00	0.00	12.3	10.2	**1.20**	**1.20**
30	25	30	0	1	1	1	**60**	0	0	0.9	21.7	0.00	0.00	0.00	12.1	10.0	**1.22**	**1.22**
30	25	30	0	1	1	1	**80**	0	0	0.9	21.7	0.00	0.00	0.00	11.9	9.8	**1.21**	**1.21**
30	25	30	0	0	0	0	0	**0.1**	0	0.7	17.8	0.05	0.57	0.00	8.6	8.9	**0.96**	**0.96**
30	25	30	0	0	0	0	0	**0.2**	0	0.7	17.8	0.20	1.13	0.00	8.2	9.1	**0.90**	**0.90**
30	25	30	0	0	0	0	0	**0.3**	0	0.7	17.8	0.44	1.70	0.00	7.8	9.3	**0.84**	**0.84**
30	25	30	0	0	0	0	0	**0.4**	0	0.7	17.8	0.78	2.27	0.00	7.4	9.6	**0.77**	**0.77**
30	25	30	0	0	0	0	0	0.1	**-50**	0.7	17.8	0.05	0.28	0.00	8.7	8.9	**0.98**	**0.98**
30	25	30	0	0	0	0	0	0.1	**-25**	0.7	17.8	0.05	0.42	0.00	8.6	8.9	**0.97**	**0.97**
30	25	30	0	0	0	0	0	0.1	**0**	0.7	17.8	0.05	0.57	0.00	8.6	8.9	**0.96**	**0.96**
30	25	30	0	0	0	0	0	0.1	**0**	0.7	17.8	0.05	0.57	0.00	8.6	8.9	**0.96**	**0.96**
30	25	30	0	0	0	0	0	0.1	**25**	0.7	17.8	0.05	0.57	0.96	8.0	8.9	**0.90**	**0.90**
30	25	30	0	0	0	0	0	0.1	**50**	0.7	17.8	0.05	0.57	1.92	7.4	8.9	**0.83**	**0.83**
30	25	30	0	0	0	0	0	0.1	**75**	0.7	17.8	0.05	0.57	2.88	6.9	8.9	**0.77**	**0.77**
30	25	30	0	0	0	0	0	0.1	**100**	0.7	17.8	0.05	0.57	3.84	6.3	8.9	**0.71**	**0.71**
α	γ	φ	c	N	T	S	β	z	ξ	Vol	Wt.	V	Ud	U'	Fr	Fd	FS	FS (*PS*)

Note: Shaded cell represents factor of safety calculated using negative drainage impedance algorithm. Used as a check for the value of 0 against the positive drainage impedance algorithm.

5.2 *WedgeSlip*

5.2.1 Wedge Example (No Tension Crack)

The following example is a case designed to utilize symmetry for ease of calculation. The wedge that is to be analyzed can be visualized as a portion of a cube. For this example, the sides of the cube are set at an arbitrary length of 2. Figure 5.3 is a schematic diagram showing the wedge geometry for this example.

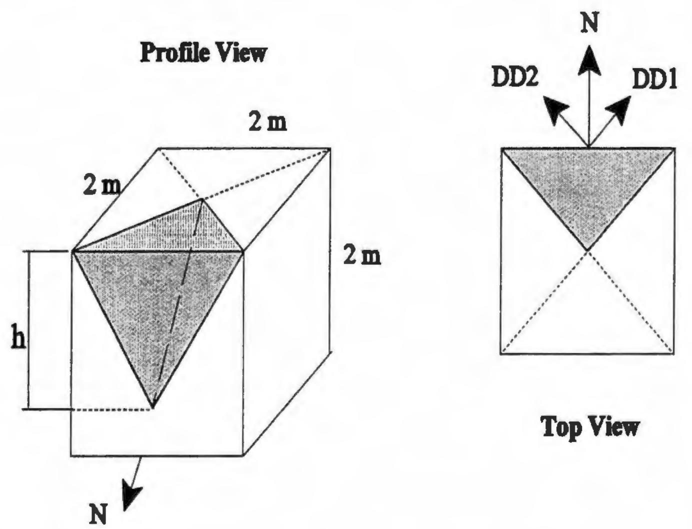


Figure 5.3 Wedge slide schematic.

Step 1. Calculate the Volume of the Wedge

The wedge can be visualized as a pyramid with variable base, h, and height of 1.

The formula for the volume of a pyramid is as follows:

Volume = $^1/_3$ * base * height = $^1/_3$ * h * 1 = h / 3

Step 2. Calculate the Weight of the Wedge

The weight of the wedge is simply its volume times the unit weight of the rock mass.

Weight of the wedge = Volume * Unit Weight (γ) = γ * h / 3

Step 3. Dip and Dip Direction of Planes

North is defined as the dip direction of the slope face. The first step is to find the relationship between the true dip, δ, and apparent dip, δ', of the two planes. The following diagram (Figure 5.4) illustrates a section of the cube. All quantities are labeled on the diagram. Thus, trigonometric relationships between the angles can be found. From the diagram, the following trigonometric relationships can be derived:

$\text{Tan}\ \delta = h / w$

$\text{Tan}\ \delta' = h / w'$

$\text{Cos}\ \beta = w / w' \Rightarrow w = w'\ \text{Cos}\ \beta$

$\therefore \text{Tan}\ \delta = h / w = h / (w' * \text{Cos}\ \beta) = \text{Tan}\ \delta' / \text{Cos}\ \beta$

For this example, $\delta' = \text{Tan}^{-1}\ h$; $\beta = 45\ °$. Therefore, $\delta = \text{Tan}^{-1}\ (h / \text{Cos}\ 45) = \text{Tan}^{-1}\ (\sqrt{2} * h)$.

Thus, we have the following dip and dip direction equations for the two planes:

Dip 1 = $\text{Tan}^{-1}\ (\sqrt{2} * h)$; Dip Direction 1 = 45 °; Dip 2 = $\text{Tan}^{-1}\ (\sqrt{2} * h)$;

Dip Direction 2 = 315 °.

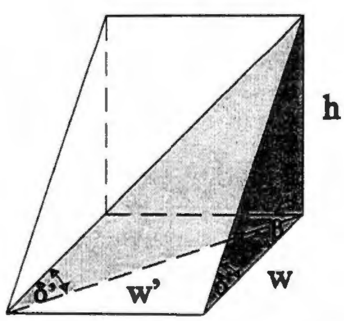


Figure 5.4 Diagram illustrating the relationship between apparent and true dip.

Step 4. Determine the Plunge of the Line of Intersection

By inspection, the plunge of the line of intersection, ψ, is equal to Tan^{-1} h.

Step 5. Determine the Dihedral Angle Between the Two Planes

The dihedral angle is measured in the plane that is perpendicular to the line of intersection. The dihedral angle (α) is equal to 2 Tan^{-1} (1 / h cos ψ).

Step 6. Determine the Normal Force for Each Plane

Since the wedge is symmetric, the normal force on each plane will be the same. Thus, the normal force for one plane is all that needs to be calculated. The breakdown of the forces acting on a plane (due to weight of the wedge) is illustrated in Figure 5.5.

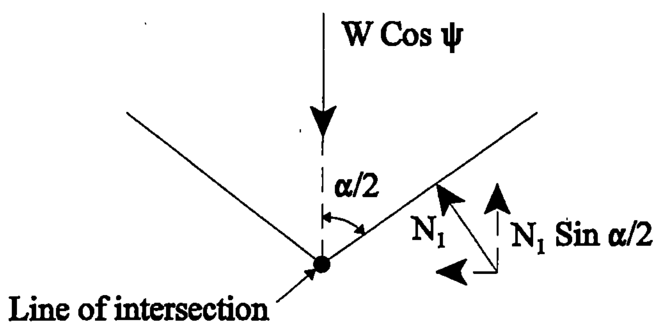


Figure 5.5 Components of forces as viewed perpendicular to the line of intersection.

Utilizing limiting equilibrium principles and symmetry, the following equalities are obtained:

$$2N_i \text{ Sin } (\alpha/2) = W \text{ Cos } \psi$$

and

$$N_i = \tfrac{1}{2} W \text{ Cos } \psi / \text{Sin } (\alpha/2)$$

Step 7. Calculation of Area of Slide Plane

The area of each plane is calculated as follows:

$$A_i = 1 / (2 * \text{Cos}\, \psi * \text{Sin}\, (\alpha/2)$$

Step 8. Determine the Normal Force for Each Plane Including Rockbolts

$$N_i(B) = \tfrac{1}{2}\, W\, \text{Cos}\, \psi / \text{Sin}\, (\alpha/2) + \tfrac{1}{2}\, N\, T\, \text{Cos}\, \beta / \text{Sin}\, (\alpha/2)$$

Step 9. Determine the Factor of Safety (With No Water Pressure)

$$FS = \frac{\text{Resisting Force}}{\text{Driving Force}} = \frac{2N_i(B)\text{Tan}\phi + 2A_i c}{W\text{Sin}\psi - nT\text{Sin}\beta}$$

Step 10. Determine the Normal Force for Each Plane Including Water Pressure

$$N_i' = Ni(B) - u_i A_i$$

Step 11. Determination of Factor of Safety Including the Effects of Water Pressure (u)

$$FS = \frac{2N_i'\text{Tan}\phi + 2A_i c}{W\text{Sin}\psi - nT\text{Sin}\beta}$$

5.2.2 Verification

The previous example was entered in *WedgeSlip* and the factor of safety acquired for several different scenarios. These were compared with spreadsheet calculations based on the previous formulas. Four iterations for each variable were run (with all other variables being held constant) and results obtained. The following spreadsheet (Table 5.2) shows the agreement between the two results and as a result, verifies the accuracy of *WedgeSlip* for this simple example.

Table 5.2 *WedgeSlip* verification exercise (see Table 3.2 for definition of variables).

WedgeSlip Verification Exercise																		
12/28/98																		
h	**Vol**	γ	**Wt.**	ψ	α	**Area**	φ	**c**	**N**	**T**	**S**	β	**u**	**N'**	**Fr**	**Fd**	**FS**	**FS (*WS*)**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	0	3.61	4.17	5.89	**0.71**	**0.71**
2	0.67	25	16.67	63.43	96.38	1.50	30	0	0	1	1	10	0	5.00	5.77	14.91	**0.39**	**0.39**
3	1.00	25	25.00	71.57	93.02	2.18	30	0	0	1	1	10	0	5.45	6.29	23.72	**0.27**	**0.27**
4	1.33	25	33.33	75.96	91.74	2.87	30	0	0	1	1	10	0	5.63	6.50	32.34	**0.20**	**0.20**
1	0.33	**26**	8.67	45.00	109.47	0.87	30	0	0	1	1	10	0	3.75	4.33	6.13	**0.71**	**0.71**
1	0.33	**27**	9.00	45.00	109.47	0.87	30	0	0	1	1	10	0	3.90	4.50	6.36	**0.71**	**0.71**
1	0.33	**28**	9.33	45.00	109.47	0.87	30	0	0	1	1	10	0	4.04	4.67	6.60	**0.71**	**0.71**
1	0.33	**29**	9.67	45.00	109.47	0.87	30	0	0	1	1	10	0	4.19	4.83	6.84	**0.71**	**0.71**
1	0.33	25	8.33	45.00	109.47	0.87	**10**	0	0	1	1	10	0	3.61	1.27	5.89	**0.22**	**0.22**
1	0.33	25	8.33	45.00	109.47	0.87	**20**	0	0	1	1	10	0	3.61	2.63	5.89	**0.45**	**0.45**
1	0.33	25	8.33	45.00	109.47	0.87	**30**	0	0	1	1	10	0	3.61	4.17	5.89	**0.71**	**0.71**
1	0.33	25	8.33	45.00	109.47	0.87	**40**	0	0	1	1	10	0	3.61	6.06	5.89	**1.03**	**1.03**
1	0.33	25	8.33	45.00	109.47	0.87	30	**5**	0	1	1	10	0	3.61	12.83	5.89	**2.18**	**2.18**
1	0.33	25	8.33	45.00	109.47	0.87	30	**10**	0	1	1	10	0	3.61	21.49	5.89	**3.65**	**3.65**
1	0.33	25	8.33	45.00	109.47	0.87	30	**15**	0	1	1	10	0	3.61	30.15	5.89	**5.12**	**5.12**
1	0.33	25	8.33	45.00	109.47	0.87	30	**20**	0	1	1	10	0	3.61	38.81	5.89	**6.59**	**6.59**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	**2**	1	1	10	0	4.81	7.56	5.55	**1.36**	**1.36**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	**4**	1	1	10	0	6.02	10.95	5.20	**2.11**	**2.11**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	**6**	1	1	10	0	7.23	14.34	4.85	**2.96**	**2.96**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	**8**	1	1	10	0	8.43	17.74	4.50	**3.94**	**3.94**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	**5**	1	10	0	6.62	8.65	5.02	**1.72**	**1.72**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	**10**	1	10	0	9.64	12.13	4.16	**2.92**	**2.92**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	**15**	1	10	0	12.65	15.61	3.29	**4.75**	**4.75**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	**20**	1	10	0	15.67	19.09	2.42	**7.89**	**7.89**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	**5**	10	0	4.21	9.86	5.72	**1.72**	**1.72**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	**10**	10	0	4.21	14.86	5.72	**2.60**	**2.60**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	**15**	10	0	4.21	19.86	5.72	**3.47**	**3.47**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	**20**	10	0	4.21	24.86	5.72	**4.35**	**4.35**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	**20**	0	4.18	5.83	5.55	**1.05**	**1.05**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	**40**	0	4.08	5.71	5.25	**1.09**	**1.09**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	**60**	0	3.91	5.52	5.03	**1.10**	**1.10**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	**80**	0	3.71	5.29	4.91	**1.08**	**1.08**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	**1**	2.74	3.17	5.89	**0.54**	**0.54**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	**2**	1.88	2.17	5.89	**0.37**	**0.37**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	**3**	1.01	1.17	5.89	**0.20**	**0.20**
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	**4**	0.14	0.17	5.89	**0.03**	**0.03**
h	**Vol**	γ	**Wt.**	ψ	α	**Area**	φ	**c**	**N**	**T**	**S**	β	**u**	**N'**	**Fr**	**Fd**	**FS**	**FS (*WS*)**

5.3 Example Data (*WedgeSlip*)

5.3.1 Introduction

Several example cases of wedge sliding analysis were performed to further validate the *WedgeSlip* program. The original data were hand plotted on a stereonet in some cases. Then the data were entered into the *WedgeSlip Version 1.3* program, results obtained, and the geometry of the slope verified. Five of these examples are actually programmed into *WedgeSlip*. They can be found under the "Data" pull-down menu in the submenu "Examples". The following table gives details of each example including source, input data and comparison between published and *WedgeSlip* results.

Table 5.3 *WedgeSlip* Example Data.

Example	1	2	3	4	5
Source	Limestone Quarry, Alabama, 1998	I-40 Wedge, Russell Glass, N.C.D.O.T., 1997	Symmetric Wedge, Dr. Matthew Mauldon, 1998	B.K. Low, 1997	TRB Special Report 247, 1996
Units	SI	fps	SI	SI	SI
ψ1	30	36	54.74	45	45
α1	244	250	315	105	265
ψ2	71	61	54.74	70	48
α2	343	161	45	235	168
ψ3	0	0	0	12	10
α3	227	212	180	185	196
ψ4	54	76	90	16	76
α4	227	212	0	185	196
H	10	200	10	30.55	30
φ1	30	30	30	30	35
φ2	30	30	30	20	35
c1	0	0	0	24	20
c2	0	0	0	48	10
u1	0	0	0	66.7	0
u2	0	0	0	66.7	0
γ	27	160	25	25	25
Sliding Mode	Single Plane Sliding on Plane1	Double Plane Sliding	Double Plane Sliding	Double Plane Sliding	Double Plane Sliding
FS (*WedgeSlip*)	1	0.95	0.71	1.32	1.18
Published FS	1	--	0.71	1.32	1.23*

* The FS published in TRB was based on angles measured graphically from a stereonet.

5.4 *RockSlip*

The verification method used for *RockSlip* is one of comparison with the symmetric case used to verify *WedgeSlip*. The height of the block, *h*, and friction angle, ϕ, are the two variables examined in this verification exercise. The shape of the slope face triangle for each wedge was determined using the results in section 5.2.1. This information was then input into *RockSlip* using a points file (*.pts). The points file is accessed by going to **File** ⇒ **Open Points**. A dialog box will appear allowing the user to browse for a points file. A points file was generated for this exercise based on the shape of the slope face triangle. The points file contains coordinates of each of the points, from right to left, which define the multi-planar failure surface. The coordinate system used to define the points is shown on the following page in Figure 5.6. The following spreadsheet (Table 5.4) shows the results of this verification exercise.

Table 5.4 *RockSlip* verification exercise.

RockSlip Verification Exercise 4/19/99				
h	**ϕ**	**FS**	**FS(*WedgeSlip*)**	**FS(*RockSlip*)**
1	30	0.71	0.71	0.71
2	30	0.39	0.39	0.40
3	30	0.27	0.27	0.28
4	30	0.20	0.20	0.20
1	10	0.22	0.22	0.22
1	20	0.45	0.45	0.45
1	30	0.71	0.71	0.71
1	40	1.03	1.03	1.03

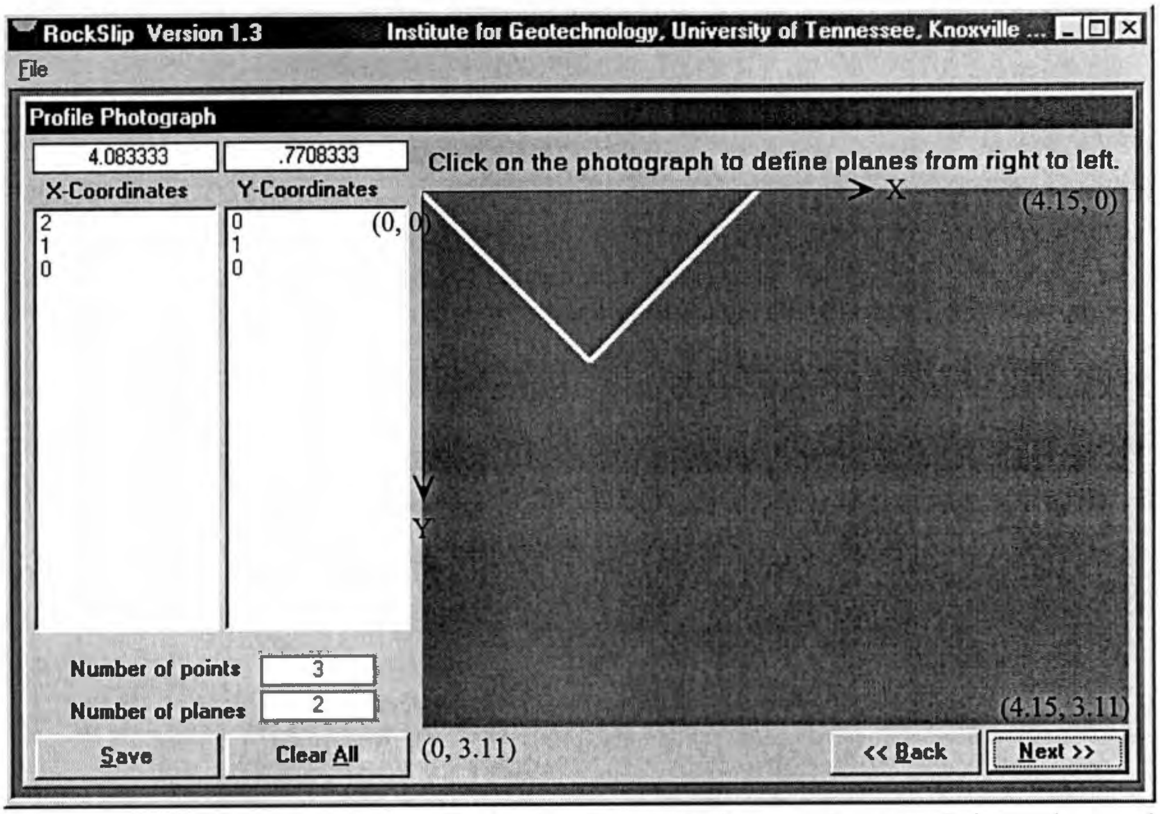


Figure 5.6 Example of points file in *RockSlip*. Relative coordinates of picture box and coordinate axes are shown.

PART VI

ALGORITHMS AND CODE - *PlaneSlip*

Note: Program code appears in `Courier New 10 point font` and code comments appear in Times New Roman 12 point font in Parts 6, 7 and 8.

6.1 Geometry

Since *PlaneSlip* calculates the factor of safety based on the cross sectional geometry of the slope (because a unit thickness of 1 is assumed). The following diagram

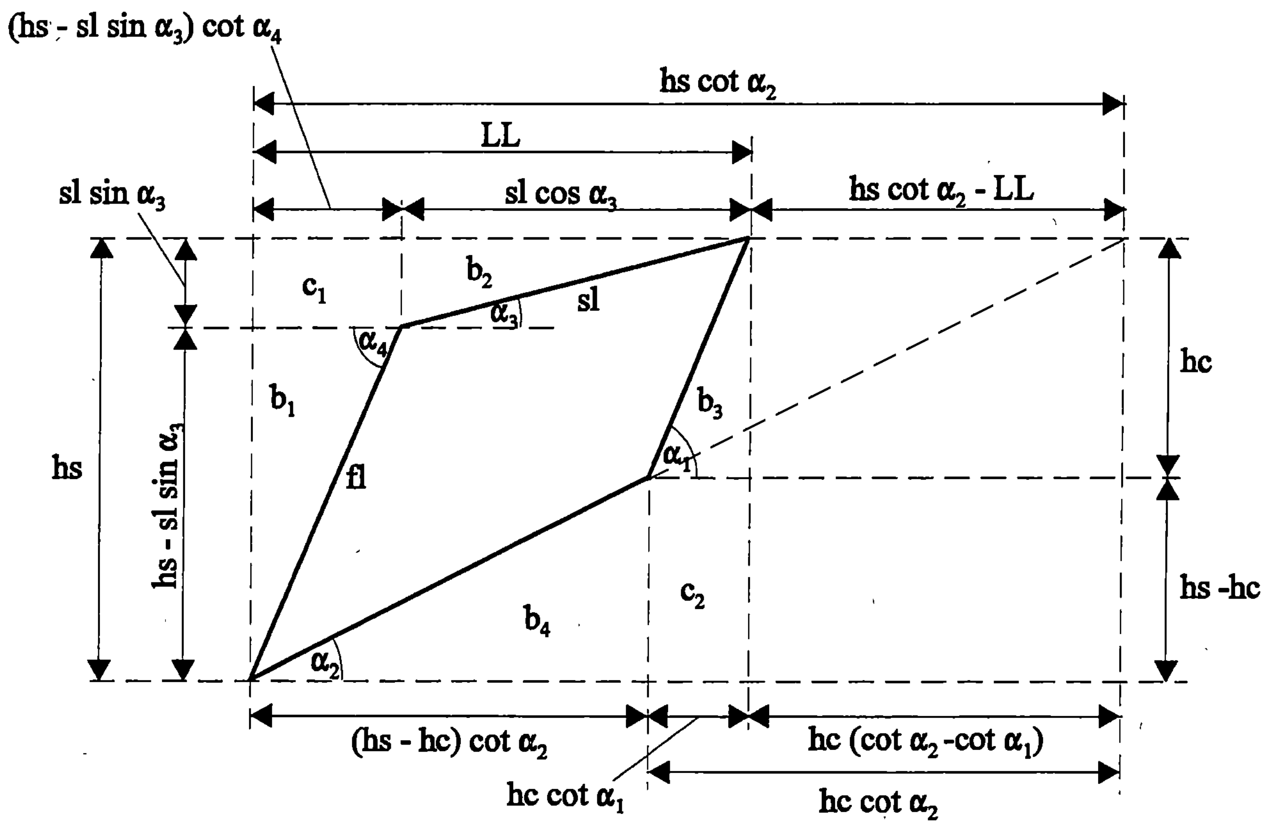


Figure 6.1 Generalized cross-section showing all geometric quantities.

(Figure 6.1) shows a typical cross section and the quantities that are used to calculate various lengths and ultimately the cross sectional area, volume, and weight of the block of rock. Three linear values are required for the calculation of the area of the cross-section; hs, the vertical distance from the lowest to the highest point of the cross section; LL, the horizontal distance from the lowest to the highest point of the cross section; hc, the height of tension crack.

The formulae for these quantities are as follows:

$$hs = fl \cdot \sin\alpha_4 + sl \cdot \sin\alpha_3$$

$$LL = fl \cdot \cos\alpha_4 + sl \cdot \cos\alpha_3$$

$$hc = \frac{(LL - hs)\cot\alpha_2}{(\cot\alpha_1 - \cot\alpha_2)}$$

The area of the cross-section is now found by taking the large rectangle with dimensions LL × hs and subtracting from it the triangles b_1 - b_4, and the rectangles c_1 and c_2. In mathematical form:

$$\text{Cross-sectional area, } a = (LL \cdot hs) - b_1 - c_1 - b_2 - b_3 - c_2 - b_4$$

where,

$$b_1 = \frac{(hs - sl\sin\alpha_3)^2}{2\tan\alpha_4}$$

$$c_1 = \frac{(sl\sin\alpha_3)(hs - sl\sin\alpha_3)}{\tan\alpha_4}$$

$$b_2 = \frac{(sl\sin\alpha_3)(sl\cos\alpha_3)}{2}$$

$$b_3 = \frac{hc^2}{2\tan\alpha_1}$$

$$c_2 = (hs - hc)\frac{hc}{\tan\alpha_1}$$

$$b_4 = \frac{(hs - hc)^2}{2\tan\alpha_2}$$

6.1.2 Program Code

```
hs = fl * Sin(q4) + sl * Sin(q3)
```

hs = the vertical distance from the lowest to the highest point of the cross section.

```
LL = fl * Cos(q4) + sl * Cos(q3)
```

LL = the horizontal distance from the lowest to the highest point of the cross section.

```
hc = (LL - hs / Tan(q2)) / (1 / Tan(q1) - 1 / Tan(q2))
```

hc = the height of tension crack.

Calculates the total volume of rock and its weight.

Rem calculate the volume (a) of block.

```
a = LL * hs
a = a - (((hs - sl * Sin(q3)) ^ 2) / (2 * Tan(q4))) b1
a = a - ((sl * Sin(q3)) * (hs - sl * Sin(q3)) / Tan(q4)) c1
a = a - ((sl ^ 2) * Sin(q3) * Cos(q3)) / 2 b2
a = a - (hc ^ 2) / (Tan(q1) * 2) b3
a = a - (hs - hc) * hc / Tan(q1) c2
a = a - (hs - hc) ^ 2 / (Tan(q2) * 2) b4
```

Rem calculate the weight of block.

```
a = a * wr    wr-- rock unit weight
```

6.2 Water Force

We consider four cases for the water pressure problem in plane failure: two extreme cases, drained and undrained; an intermediate partially drained case; and a case with negative drainage impedance. The drained case has a fully drained toe and the undrained case has no drainage at the toe. For the intermediate case, (between drained case and undrained case), we use a parameter called "Drainage Impedance" to adjust drainage percentage at the toe. Negative drainage impedance is used to model cases where water reaches atmospheric pressure before it reaches the toe of the slope. This can be a result of erosion or block rotation opening up the slide plane. The geometry of a typical plane failure is shown in Fig.6.2(a). We assume that water pressure has a distribution shown in Fig. 6.2(b). In Fig. 6.2(b), line *deafo* illustrates the pressure distribution in the drained case, and *deafgo* for the Winter case and *deafg'o* for the partially drained case. When Drainage Impedance is equal to 100%, the water pressure

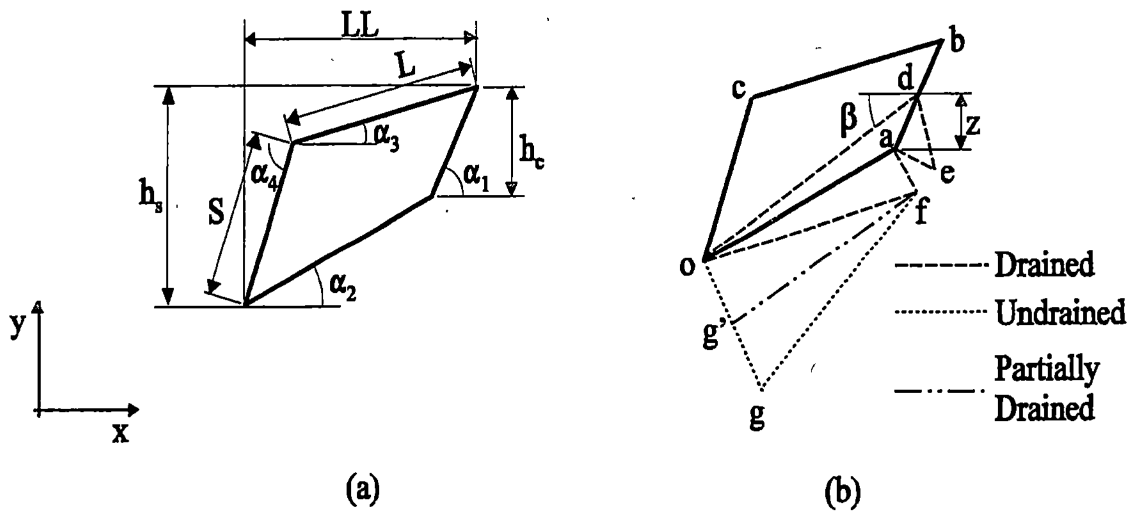


Figure 6.2 Cross-section of a plane slide showing geometric variables.

distribution is equivalent to that of the undrained case. When Drainage Impedance is equal to 0% , the water pressure distribution is equivalent to that of the drained case. In the discussion of wedge failure and prismatic failure, we still use Drainage Impedance to describe the intermediate case. Later we don't repeat this again. Now let's calculate the total water force in the above three cases.

6.2.1 Drained Case

We use V to represent the total water force acting on line *ad*, U the total force on *oa*. Let γ denote the unit weight of water, and let z denote the height of water in the tension crack. Then we have

$$|V| = \tfrac{1}{2} \times z \times ad \times \gamma \quad (6.1)$$

$$|U| = \tfrac{1}{2} \times z \times oa \times \gamma \quad (6.2)$$

$$V_x = -(\tfrac{1}{2} \times z \times ad \times \gamma) \times \sin \alpha_1 \quad (6.3)$$

$$V_y = (\tfrac{1}{2} \times z \times ad \times \gamma) \times \cos \alpha_1 \quad (6.4)$$

$$U_x = -(\tfrac{1}{2} \times z \times oa \times \gamma) \times \sin \alpha_2 \quad (6.5)$$

$$U_y = (\tfrac{1}{2} \times z \times oa \times \gamma) \times \cos \alpha_2 \quad (6.6)$$

The magnitude of the total water force, F^D, acting on the block is

$$|F^D| = [(V_x + U_x)^2 + (V_y + U_y)^2]^{1/2}$$

$$= (z \times \gamma/2) \times [(ad \times \sin \alpha_1 + oa \times \sin \alpha_2)^2 + (ad \times \cos \alpha_1 + oa \times \cos \alpha_2)^2]^{1/2}$$

$$= (z \times \gamma/2) \times od. \quad (6.7)$$

Using the result,

$$(V_x + U_x) / (V_y + U_y) = (ad \times \sin \alpha_1 + oa \times \sin \alpha_2) / (ad \times \cos \alpha_1 + oa \times \cos \alpha_2)$$

$= \tan(\beta)$, we note that the total water force F^D

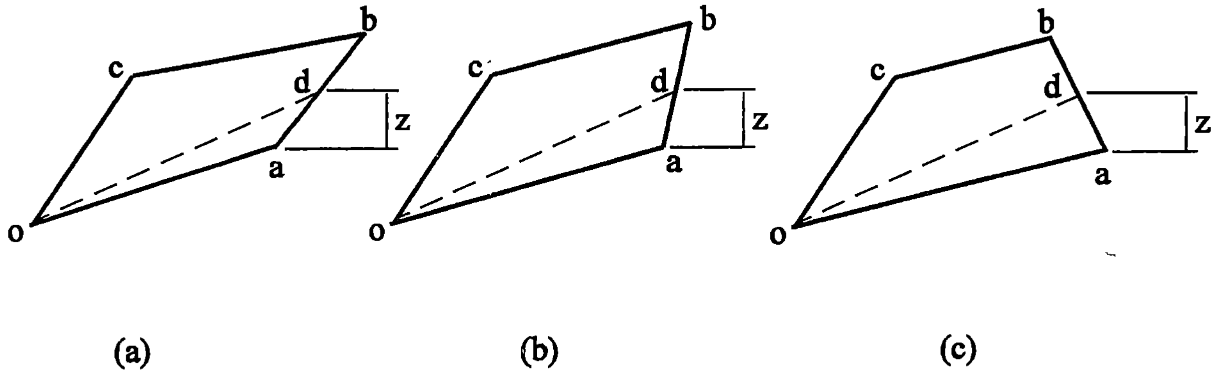


Figure 6.3 **Cross-section showing independence of F^D on shape of block oabc.**

is perpendicular to *od*. Furthermore, the magnitude of the water force depends only on the height, z, of water in the tension crack and the length of *od*. This is an interesting result. It means that if *z* and line *od* are not changed, the shape of block *oabc* has no influence on F^D, i.e. F^D for several shapes in Fig.6.3 has the same value.

6.2.3 Undrained Case

For the undrained case, we can divide the water force into two parts: one is just the water pressure of the drained case, another is that formed by the water pressure of Δofg in Fig. 6.2(b).

Total water force formed by the part of Δofg in Fig. 6.2(b), we name it F', is equal to

$$|F'| = \frac{1}{2} \times \gamma_w \times (hs - hc + z) \times (hs - hc)/\sin\alpha_2 \qquad \textbf{(6.8)}$$

where $hs - hc + z$ is the pressure head at point o and $(hs - hc)/\sin\alpha_2$ is the length *oa* of the slide plane.

From the geometry in Figure 6.1, we have

$hs = S \times sin\ \alpha_4 + L \times sin\ \alpha_3$, and

$hc = (S \times sin\ \alpha_4 + L \times sin\ \alpha_3)(1 - 1/(n\text{-}m)) - n(S \times cos\ \alpha_4 + L \times cos\ \alpha_3)(1 - n/(n\text{-}m))$

the direction of ***F'*** is perpendicular to line *oa*, therefore the total water force, $\boldsymbol{F^U}$, for the undrained case is

$$\boldsymbol{F^U = F' + F^D} \qquad \textbf{(6.9)}$$

6.2.4 Partially Drained Case

In this case, we keep the water force of the drained case as a basic part, which doesn't change with Drainage Impedance, and just use Drainage Impedance to modify ***F'*** in Eq.(6.8) by formulae

$$\boldsymbol{F^{DI} = F'} \times \xi \qquad \textbf{(6.10)}$$

where $\boldsymbol{F^{DI}}$ is the water force of Δofg including the modification for Drainage Impedance.

ξ is Drainage Impedance and has a range of 0 to 100% for positive values.

Then the total water force ***F*** is

$$\boldsymbol{F = F^D + F^{DI}} \qquad \textbf{(6.11)}$$

6.2.5 Negative Drainage Impedance

Negative drainage impedance is used to model situations where water reaches atmospheric pressure at a point back into the slope along the slide plane. *PlaneSlip* handles the calculation of the appropriate uplift force on the slide plane by modifying the point where the pressure distribution goes to zero according to the amount of drainage impedance. For instance, if the drainage impedance is set to - 50%, then the water pressure distribution goes to zero at a point halfway along the length of the slide plane. In turn this reduces the magnitude of the water force acting on the slide plane and increases the factor of safety. Negative drainage impedance has a range of -1% to -90%.

6.2.6 Program Code

The code used in *PlaneSlip* to calculate the water force is listed below. Overall, the code follows the algorithms outlined in the previous sections for calculating the water force in each case. Some differences exist in the variable names and the order in which quantities are calculated. Also, the code contains the logical operators used to distinguish between the different cases and in some instances, the different slope geometries that are possible.

```
Rem if zw=0, no water
    If zw = 0 Then
        GoTo 100
    End If

    If zw > hc Then
        GoTo 200
    '-->> Old code: GoTo 50
    End If
```

Rem calculate water force

```
If xi >= 0 Then ' This block is for drainage impedance >= 0

  Lc = zw / Tan(q1) + (hs - hc) / Tan(q2)
'Lc is the length of line od in Figure 6.3;
'also Xd in alternate coordinate system
  qL = (hs - hc + zw) / Lc
    qL = Atn(qL) ' dip angle of water plane od

' qL is the dip angle of water plane od in Figure 6.3

  Lc = Sqr(Lc ^ 2 + ((hs - hc + zw) ^ 2)) 'length of od

    a1 = Lc * zw / 2 * ww
' = 1/2 * unit weight of water * zw = fictitious force, W, on water plane

  rn = rn - a1 * Cos(qL - q2) ' normal force on sliding plane
  rt = rt + a1 * Sin(qL - q2) ' shear force on sliding plane
```

Rem water force in winter

```
'xi = drainage impedance
  rn = rn - ((hs - hc + zw) * xi * (hs - hc) / Sin(q2) / 2 * ww)
```

```
Else ' This block is for drainage impedance < 0.

  Dim lsp, u, v, vn, vt, quv As Single

' lsp = length of slide plane, u = uplift force on sliding plane

' v = force on tension crack, vn = normal (to sliding plane) component of v

' vt = tangential (to sliding plane) component of v, quv = angle between forces u and v

    lsp = (((hs - hc) ^ 2) + (((hs - hc) / Tan(q2)) ^ 2)) ^ (1 / 2)

    u = ((1 + xi) * lsp * zw * ww) / 2

    v = ((zw ^ 2) * ww) / 2

    quv = q11 - q22

    quv = quv * r

    vn = v * Cos(quv)

    vt = v * Sin(quv)

    rn = rn - u - vn ' normal force

    rt = rt + vt ' driving force

End If
```

6.3 Factor of Safety

6.3.1 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. Thus, one must define an index which describes the relationship between driving and resisting forces for each geometric and mechanical situation in a rock slope. This is traditionally done using an index called the *Factor of Safety*. The Factor of Safety is most commonly defined as the ratio of the total resisting force to the total driving force. For plane sliding, the equation for calculating the Factor of Safety is as follows:

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi}{W\sin\psi_p + V\cos\psi_p} \tag{6.12}$$

Where FS = factor of safety, c = cohesion, A = area of failure surface, W = weight of rock, ψ_p = slope of failure plane, U = uplift water force on failure plane, V = water force on tension crack, and ϕ = friction angle. All notation is consistent with Hoek & Bray (1981).

The above equation includes the effects of water pressure but does not address the effects of rock reinforcement. If a rock bolt or cable is oriented as shown in Figure 2.4, then the equation is modified as follows:

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p + N_b F_b\cos\beta)\tan\phi + N_b S_b / S_h}{W\sin\psi_p + V\cos\psi_p - N_b F_b\sin\beta} \tag{6.13}$$

Where N_b = number of rockbolts, F_b = cable or bolt tension, S_b = shear strength of bolts, S_h = horizontal spacing of rockbolts and β = angle cable or bolt makes with normal to failure plane. Note that β can be calculated indirectly from the dips of the face and failure plane and the angle, θ, that the rockbolt makes with the normal to the face (this quantity is easily measured in the field and is also the type of information that needs to be conveyed to a driller who is installing the rockbolts). The following is the formulation of β that is used in the *PlaneSlip* computer code:

$$\beta = \psi_f - \psi_p - \theta \tag{6.14}$$

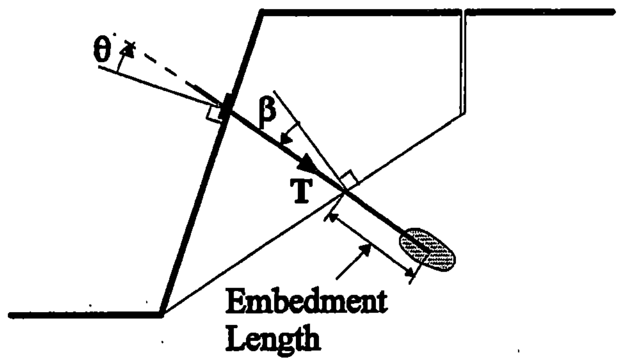


Figure 6.4 Plane slide schematic defining the orientation of a rock bolt or cable.

6.3.2 Program Code

The code used in *PlaneSlip* to calculate the factor of safety is listed below. Overall, the code follows the algorithms outlined in the previous section for calculating the factor of safety in each case. Some differences exist in the variable names and the order in which quantities are calculated. Also, the code contains the logical operators used to distinguish between the different cases and in some instances, the different slope geometries that are possible.

Rem calculate the factor of safety

```
Dim f0, fs2, fs5 As Single
100 If rt <= 0 Then GoTo 200
    f0 = (hs - hc) * c / Sin(q2) + rn * Sin(qc) / Cos(qc) + rt1 + SF *
(NB - jj)
    fs = f0 / rt
    If fs < 0 Then fs = 0
```

Formats the factor of safety to 2 decimal places and 5 decimal places.

```
fs2 = Format(fs, "0.00")

fs5 = Format(fs, "0.00000")
```

Rem display information on input data(whether they are correct?)

```
200 picBox.PSet (0, 0), vbWhite
    If hc < 0 Then
        txtResults.Text = "data entry wrong"
        Exit Sub
    Else
    If rt <= 0 Then ' driving force acts upward, very safe!
txtResults.Text = "driving force acting upward (factor of safety not
defined)"
        Exit Sub
    End If
```

Display factor of safety.

```
        txtResults.Text = "Factor of Safety = " & CSng(fs2) & " (" &
CSng(fs5) & ")"
     End If
```

PART VII

ALGORITHMS AND CODE - *WedgeSlip*

ALGORITHMS AND CODE - *WedgeSlip*

Note: The coordinate system used is y is north, x is east and z is vertically up. The variables used in the computer code correspond to the variables used by Hoek & Bray in *Rock Slope Engineering* (1981). The following is a list of those variables.

1. $\mathbf{a} = \mathbf{n}_1$ = unit normal vector for plane 1 (positive up)
2. $\mathbf{b} = \mathbf{n}_2$ = unit normal vector for plane 2 (positive up)
3. $\mathbf{d} = \mathbf{n}_3$ = unit normal vector for plane 3 (upper ground surface) (positive up)
4. $\mathbf{f} = \mathbf{n}_4$ = unit normal vector for plane 4 (slope face) (positive up)
5. $\mathbf{f}_5 = \mathbf{n}_5$ = unit normal vector for plane 5 (tension crack) (positive up)
6. $\mathbf{t}$ = rock bolt vector (positive down)
7. $\mathbf{e}$ = external force vector (positive down)
8. $\mathbf{g} = \mathbf{f} \times \mathbf{a} = \mathbf{n}_4 \times \mathbf{n}_1 = \sin\theta_{n1.n4}$
9. $\mathbf{g}_5 = \mathbf{f}_5 \times \mathbf{a} = \mathbf{n}_5 \times \mathbf{n}_1 = \sin\theta_{n1.n5}$
10. $\mathbf{i} = \mathbf{b} \times \mathbf{a} = \mathbf{n}_2 \times \mathbf{n}_1 = \sin\theta_{n1.n2}$
11. $\mathbf{j} = \mathbf{f} \times \mathbf{d} = \mathbf{n}_4 \times \mathbf{n}_3 = \sin\theta_{n3.n4}$
12. $\mathbf{j}_5 = \mathbf{f}_5 \times \mathbf{d} = \mathbf{n}_5 \times \mathbf{n}_3 = \sin\theta_{n3.n5}$
13. $\mathbf{k} = \mathbf{i} \times \mathbf{b} = (\mathbf{b} \times \mathbf{a}) \times \mathbf{b} = \mathbf{a} - \mathbf{b}(\mathbf{a} \cdot \mathbf{b}) = \mathbf{a} - \mathbf{b} \cdot \mathbf{r}$
14. $\mathbf{l} = \mathbf{i} \times \mathbf{a} = \mathbf{a} \times (\mathbf{b} \times \mathbf{a}) = \mathbf{b} - \mathbf{a}(\mathbf{a} \cdot \mathbf{b}) = \mathbf{b} - \mathbf{a} \cdot \mathbf{r}$
15. $\mathbf{m} = \mathbf{g} \cdot \mathbf{d} = \mathbf{f} \times \mathbf{a} \cdot \mathbf{d} = \mathbf{n}_4 \times \mathbf{n}_1 \cdot \mathbf{n}_3 = \sin\theta_{I14.I31} * \sin\theta_{n1.n4} * \sin\theta_{n1.n3}$
16. $\mathbf{m}_5 = \mathbf{g}_5 \cdot \mathbf{d} = \mathbf{f}_5 \times \mathbf{a} \cdot \mathbf{d} = \mathbf{n}_5 \times \mathbf{n}_1 \cdot \mathbf{n}_3 = \sin\theta_{I15.I31} * \sin\theta_{n1.n3} * \sin\theta_{n1.n5}$
17. $\mathbf{n} = \mathbf{b} \cdot \mathbf{j} = \mathbf{b} \cdot \mathbf{f} \times \mathbf{d} = \mathbf{n}_2 \cdot \mathbf{n}_4 \times \mathbf{n}_3 = \sin\theta_{n3.n4} * \cos\theta_{I34.n2}$

18. $\mathbf{n}_5 = \mathbf{b} \cdot \mathbf{j}_5 = \mathbf{b} \cdot \mathbf{f}_5 \times \mathbf{d} = \mathbf{n}_2 \cdot \mathbf{n}_5 \times \mathbf{n}_3 = \sin\theta_{n3.n5} * \cos\theta_{I35.n2}$

19. $\mathbf{p} = \mathbf{i} \cdot \mathbf{d} = \mathbf{b} \times \mathbf{a} \cdot \mathbf{d} = \mathbf{n}_2 \times \mathbf{n}_1 \cdot \mathbf{n}_3 = \sin\theta_{n1.n2} * \cos\theta_{I12.n3}$

20. $\mathbf{q} = \mathbf{b} \cdot \mathbf{g} = \mathbf{b} \cdot \mathbf{f} \times \mathbf{a} = \mathbf{n}_2 \cdot \mathbf{n}_4 \times \mathbf{n}_1 = \sin\theta_{n1.n4} * \cos\theta_{I14.n2}$

21. $\mathbf{q}_5 = \mathbf{b} \cdot \mathbf{g}_5 = \mathbf{b} \cdot \mathbf{f}_5 \times \mathbf{a} = \mathbf{n}_2 \cdot \mathbf{n}_5 \times \mathbf{n}_1 = \sin\theta_{n1.n5} * \cos\theta_{I15.n2}$

22. $\mathbf{r} = \mathbf{a} \cdot \mathbf{b} = \cos\theta_{n1.n2}$

23. $\mathbf{s} = \mathbf{a} \cdot \mathbf{t} = \cos\theta_{n1.t}$

24. $\mathbf{v} = \mathbf{b} \cdot \mathbf{t} = \cos\theta_{n1.t}$

25. $\mathbf{w} = \mathbf{b} \cdot \mathbf{t} = \sin\theta_{n1.n2} * (1) * \cos\theta_{I12.t}$

26. $\mathbf{s}_e$ = NOT USED

27. $\mathbf{v}_e$ = NOT USED

28. $\mathbf{w}_e$ = NOT USED

29. $\mathbf{s}_5 = \mathbf{a} \cdot \mathbf{f}_5 = \cos\theta_{n1.n5}$

30. $\mathbf{v}_5 = \mathbf{b} \cdot \mathbf{f}_5 = \cos\theta_{n2.n5}$

31. $\mathbf{w}_5 = \mathbf{i} \cdot \mathbf{f}_5 = \sin\theta_{n1.n2} * (1) * \cos\theta_{I12.n5}$

32. $\lambda = \mathbf{i} \cdot \mathbf{g} = \sin\theta_{n1.n2} * \sin\theta_{n1.n4} * \cos\theta_{I12.I14}$

33. $\lambda_5 = \mathbf{i} \cdot \mathbf{g}_5 = \sin\theta_{n1.n2} * \sin\theta_{n1.n5} * \cos\theta_{I12.I15}$

34. $\varepsilon = \mathbf{f} \cdot \mathbf{f}_5 = \cos\theta_{n4.n5}$

35. $\mathbf{R} = (1 - r^2)^{1/2} = |\sin\theta_{n1.n2}|$

36. $\rho = (1 / \mathbf{R}^2) * (\mathbf{nq} / |\mathbf{nq}|) = \pm 1 / \sin^2\theta_{n1.n2}$

37. $\mu = (1 / \mathbf{R}^2) * (\mathbf{mq} / |\mathbf{mq}|) = \pm 1 / \sin^2\theta_{n1.n2}$

38. $\nu = (1 / \mathbf{R}) * (\mathbf{p} / |\mathbf{p}|) = \pm 1 / |\sin\theta_{n1.n2}|$

39. $\mathbf{G} = |\mathbf{g}| = |\sin\theta_{n1.n4}|$

40. $\mathbf{G}_5 = |\mathbf{g}_5| = |\sin\theta_{n1.n5}|$

7.1 Geometry

WedgeSlip calculates two major sets of data: The coordinates of important points on the wedge and areas of the faces of the wedge.

7.1.1 Coordinates

Point coordinates are determined by using the unit normal vectors which describe each plane in the wedge in simultaneous plane equations which are solved to find the intersection point of the three planes. The formulation for point G will be presented here as an example calculation.

Point G

Plane 6 is defined as a vertical plane through I_{12} (shaded plane in Figure 3.4).

The unit normal vector for Plane 6 is as follows:

$$n_6 = (6_x, 6_y, 6_z) = \frac{(-i_y, i_x, 0)}{\sqrt{i_y^2 + i_x^2}}$$

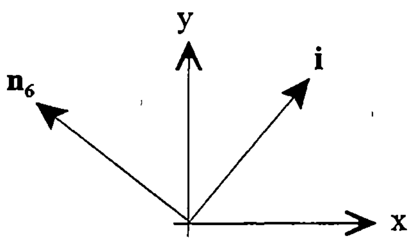


Figure 7.1 Coordinate axes showing relationship between **i** and **n**$_6$.

Coordinates of Point G = Intersection of planes 3, 4 & 6

$$\text{Coordinates of Point G} = \begin{Bmatrix} 6_x x & 6_y y & 6_z z & 0 \\ f_x x & f_y y & f_z z = & 0 \\ 0 & 0 & 1 & H \end{Bmatrix}$$

Using Cramer's Rule,

$$A = \begin{vmatrix} -i_y & i_x & 0 \\ f_x & f_y & f_z \\ 0 & 0 & 1 \end{vmatrix} = -i_y(f_y) - i_x(f_x)$$

$$A_1 = \begin{vmatrix} 0 & i_x & 0 \\ 0 & f_y & f_z \\ H & 0 & 1 \end{vmatrix} = i_x(f_z H)$$

$$A_2 = \begin{vmatrix} -i_y & 0 & 0 \\ f_x & 0 & f_z \\ 0 & H & 1 \end{vmatrix} = i_y(f_z H)$$

$$x\_coord\_G = \frac{A_1}{A} = \frac{-i_x f_z}{i_y f_y + i_x f_x} \cdot H$$

$$x\_coord\_G = \frac{-f_z}{f_x + f_y\left(\frac{i_y}{i_x}\right)} \cdot H$$

$$y\_coord\_G = \frac{A_2}{A} = x\_coord\_G \cdot \frac{i_y}{i_x}$$

$$z\_coord\_G = H$$

Point G (alternative solution, used in conjunction with previous equation to obtain coordinates of point G)

$$\begin{cases} d_x x & d_y y & d_z z & H_2 \\ f_x x & f_y y & f_z z = & 0 \\ 6_x x & 6_y y & 6_z z & 0 \end{cases} \begin{matrix} \text{Plane 3} \\ \text{Plane 4} \\ \text{Plane 6} \end{matrix}$$

$$A = \begin{vmatrix} d_x & d_y & d_z \\ f_x & f_y & f_z \\ -i_y & i_x & 0 \end{vmatrix} = -d_x f_z i_x - d_y f_z i_y + d_z\left(f_x i_x + f_y i_y\right)$$

$$A_1 = \begin{vmatrix} H_2 & d_y & d_z \\ 0 & f_y & f_z \\ 0 & i_x & 0 \end{vmatrix} = H_2\left(-f_z i_x\right)$$

$$A_2 = \begin{vmatrix} d_x & H_2 & d_z \\ f_x & 0 & f_z \\ -i_y & 0 & 0 \end{vmatrix} = -H_2\left(f_z i_y\right)$$

$$A_3 = \begin{vmatrix} d_x & d_y & H_2 \\ f_x & f_y & 0 \\ -i_y & i_x & 0 \end{vmatrix} = H_2\left(f_x i_x + f_y i_y\right)$$

$$\text{x\_coord\_G} = \frac{A_1}{A} = \frac{H_2 f_z i_x}{d_x f_z i_x + d_y f_z i_y - d_z\left(f_x i_x + f_y i_y\right)}$$

From previous calculations, $\text{x\_coord\_G} = \dfrac{-i_x f_z H}{\left(i_y f_y + i_x f_x\right)}$

Equate the two formulas for x_coord_G to obtain,

$$H_2 = \frac{\left(-i_x f_z H\right)\cdot\left(d_x f_z i_x + d_y f_z i_y - d_z\left(f_x i_x + f_y i_y\right)\right)}{\left(i_y f_y + i_x f_x\right)\cdot\left(f_z i_x\right)}$$

7.1.1.1 Program Code

```
x_coord_g = -fz * HHV / (fx + fy * iy / ix)

y_coord_g = iy / ix * x_coord_g

H2 = -dx * fz / (fx + fy * iy / ix)

H2 = H2 - dy * iy * fz / ix / (fx + fy * iy / ix) + dz
```

7.1.2 Areas

The formulas used to calculate the area of different wedge faces are based on methods outlined in Hoek & Bray's discussion of wedge failure (1981). The following is a proof of the area calculation for plane 1 (Triangle AOC).

Triangle AOC (Area of Plane 1)

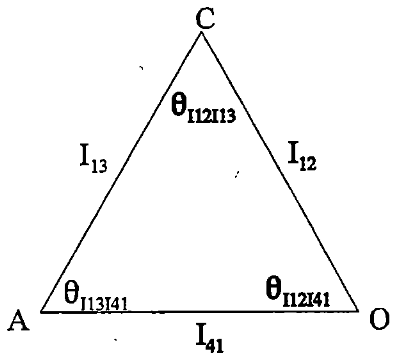


Figure 7.2 Schematic of plane 1 showing geometric quantities.

1. Calculate the three included angles.

$$\left|(n_4 \times n_1) \times (n_1 \times n_3)\right| = \sin\theta_{n_4.n_1} \sin\theta_{n_1.n_3} \sin\theta_{I_{41}.I_{13}}$$

$$\text{Also,} (n_4 \times n_1) \times (n_1 \times n_3) = n_1(n_4 \cdot n_1 \times n_3) - n_3(n_1 \cdot n_1 \times n_4) = n_1(n_4 \cdot n_1 \times n_3) = n_1 m$$

$$\therefore |m| = \sin\theta_{n_4.n_1} \sin\theta_{n_1.n_3} \sin\theta_{I_{41}.I_{13}} \text{ and } m = (n_4 \cdot n_1 \times n_3)$$

$$\left|(n_2 \times n_1) \times (n_1 \times n_3)\right| = \sin\theta_{n_2.n_1} \sin\theta_{n_1.n_3} \sin\theta_{I_{21}.I_{13}}$$

$$\text{Also,} (n_2 \times n_1) \times (n_1 \times n_3) = n_1(n_2 \cdot n_1 \times n_3) = n_1 p$$

$$\therefore |p| = \sin\theta_{n_2.n_1} \sin\theta_{n_1.n_3} \sin\theta_{I_{21}.I_{13}} \text{ and } p = (n_2 \cdot n_1 \times n_3)$$

$$\left|(n_2 \times n_1) \times (n_1 \times n_4)\right| = \sin\theta_{n_2.n_1} \sin\theta_{n_1.n_4} \sin\theta_{I_{21}.I_{14}}$$

$$\text{Also,} (n_2 \times n_1) \times (n_1 \times n_4) = n_1(n_1 \cdot n_2 \times n_4) = n_1 q$$

$$\therefore |q| = \sin\theta_{n_2.n_1} \sin\theta_{n_1.n_4} \sin\theta_{I_{21}.I_{14}} \text{ and } q = (n_1 \cdot n_2 \times n_4)$$

2. Calculate the side lengths.

By definition (line 43, H&B) $h = H_1 / |g_z|$. Note that $|g_z| = g \sin \psi_g$ where ψ_g is the plunge of g.

$$\frac{H_1}{|g_z|} = \frac{H_1}{\sin\varphi_g} \cdot \frac{1}{|g|} = |OA| \cdot \frac{1}{\sin\theta_{n_4.n_1}} = h, \text{ so that}$$

$$\underline{\underline{|OA| = h \cdot \sin\theta_{n_4.n_1}}}$$

$$|OC| = |OA| \frac{\sin\theta_{I_{13}I_{41}}}{\sin\theta_{I_{21}I_{13}}} = h\sin\theta_{n_4n_1} \cdot \frac{m}{\sin\theta_{n_1n_3}\sin\theta_{n_4n_1}} \cdot \frac{\sin\theta_{n_1n_3}\sin\theta_{n_2n_1}}{p}$$

$$\underline{\underline{|OC| = \frac{hm}{p}\sin\theta_{n_2n_1}}}$$

$$|AC| = |OA| \cdot \frac{\sin\theta_{I_{21}I_{41}}}{\sin\theta_{I_{21}I_{13}}} = h\sin\theta_{n_4n_1} \cdot \frac{q}{\sin\theta_{n_2n_1}\sin\theta_{n_4n_1}} \cdot \frac{\sin\theta_{n_2n_1}\sin\theta_{n_1n_3}}{p}$$

$$\underline{\underline{|AC| = \frac{hq}{p}\sin\theta_{n_1n_3}}}$$

3. Area of triangle AOC.

$$\text{Area AOC} = \frac{1}{2}|OA|^2 \frac{\sin\theta_{I_{13}I_{41}}\sin\theta_{I_{21}I_{41}}}{\sin\theta_{I_{13}I_{21}}} = \frac{1}{2}|OA|^2 \frac{mq}{p} \frac{1}{\sin^2\theta_{n_4n_1}}$$

Substituting the previous definition of $|OA|$, ($|OA| = h\sin\theta_{n_4n_1}$)

$$AOC = \frac{1}{2}h^2 \frac{\sin^2\theta_{n_4n_1}}{\sin^2\theta_{n_4n_1}} \frac{mq}{p}$$

$$\underline{\underline{AOC = \frac{h^2mq}{2p}}}$$

7.1.2.1 Program Code

```
A1 = (Abs(m * q) * h ^ 2) - (Abs(m5 * q5) * h5 ^ 2)

A1 = A1 / (2 * Abs(p))
```

7.2 Water Force

The method used in *WedgeSlip* to calculate the average water pressure on planes 1 and 2 is taken from Hoek & Bray (1981). The pressure distribution can be visualized as a pyramid on each plane. The formula for the average water pressures, u_1 and u_2, is as follows:

$$u_1 = u_2 = \frac{1}{3} \times \left(\gamma_w \times \frac{H}{2}\right) = \frac{(\gamma_w \times H)}{6} \qquad (7.1)$$

7.2.2 Program Code

The code used in *WedgeSlip* to calculate the water force is listed below. Overall, the code follows the algorithms outlined in the previous section for calculating the water force. Some differences exist in the variable names and the order in which quantities are calculated. Also, the code contains the logical operators used to distinguish between the different cases and in some instances, the different slope geometries that are possible.

rw = unit weight of water, HHV = H

```
u1 = (rw × HHV) / 6

u2 = (rw × HHV) / 6
```

7.3 Factor of Safety

7.3.1 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. Thus, one must define an index which describes the relationship between driving and resisting forces for each geometric and mechanical situation in a rock slope. This is traditionally done using an index called the *Factor of Safety*. The Factor of Safety is most commonly defined as the ratio of the total resisting force to the total driving force. For wedge sliding, the equation for calculating the Factor of Safety is as follows:

$$FS = \frac{(N_1 + N_2)\tan\phi + (c_1A_1 + c_2A_2)}{W * \mathrm{Sin}\varphi_i} \qquad (7.2)$$

where N_1 and N_2 are the normal forces on planes 1 and 2, respectively, c_1 and c_2 are the cohesive strengths of planes 1 and 2, A_1 and A_2 are the areas of planes 1 and 2, W is the weight of the wedge and ψ_i is the plunge of the line of intersection. If water pressure and rock bolts are included the factor of safety equation becomes:

$$FS = \frac{[(N_1 - u_1A_1) + (N_2 - u_2A_2) + N_bF_b]\tan\phi + N_bS_b + (c_1A_1 + c_2A_2)}{W * \mathrm{Sin}\varphi_i} \qquad (7.3)$$

where u_1 and u_2 are the average water pressures on planes 1 and 2, N_b is the number of rock bolts, F_b is the tensile strength of the rock bolts and S_b is the shear strength of the rock bolts.

7.3.2 Program Code

The code used in *WedgeSlip* to calculate the factor of safety is listed below. Overall, the code follows the algorithms outlined in the previous section for calculating the factor of safety in each case. Some differences exist in the variable names and the order in which quantities are calculated. Also, the code contains the logical operators used to distinguish between the different cases and in some instances, the different slope geometries that are possible.

Effective normal reactions on planes 1 and 2 assuming contact on both planes.

```
100  Dim N1, N2 As Single
```

Notation used in H&B:

--'

N1 = cw * kz + T * (r * v - s) + E * (r * ve - se) + cv * (r * v5 - s5)

N1 = rho * N1 - u1 * A1

N2 = cw * zz + T * (r * s - v) + E * (r * se - ve) + cv * (r * s5 - v5)

N2 = mu * N2 - u2 * A2

'--'

Ni means the same as in H&B (effective normal reactions).

```
   N1 = cw * kz + T * (r * v - s)
   N1 = rho * N1 - U1 * A1
   N2 = cw * zz + T * (r * s - v)
```

```
N2 = mu * N2 - U2 * A2
```

Factor of safety when N1<0 AND N2<0 (no contact maintained).

```
Dim message1, message2 As String

message1 = ""

If N1 < 0 And N2 < 0 Then
   fs = 0
   message1 = "Normal forces are negative"
   message2 = "on planes 1 & 2."
End If
```

If N1>0 AND N2<0, contact is maintained on plane 1 only and the factor of safety is calculated as follows.

```
If N1 > 0 And N2 < 0 Then
```

From H&B:

----

cna = cw * az - T * s - E * se -cv * s5 - u2 * A2 * r

csx = -(T * tx + E * ex + cna * ax + v * f5x + u2 * A2 * bx)

csy = -(T * ty + E * ey + cna * ay + v * f5y + u2 * A2 * By)

csz = -(T * tz + E * ez + cna * az + v * f5z + u2 * A2 * bz) + cw

csa = Sqr(csx ^ 2 + csy ^ 2 + csz ^ 2)

cqa = (cna - u1 * A1) * Tan(phi1) + c1 * A1

All variables mean same as in H&B.

```
Dim cna, cna2, csx, csy, csz, csa, cqa As Single

sliding_mode = 1
```

cna = cw * az - T * s - ((U2 * A2 * r) * (p / Abs(p)))

csx = -(T * tx + cna * ax + ((U2 * A2 * bx) * (p / Abs(p))))

csy = -(T * ty + cna * ay + ((U2 * A2 * by) * (p / Abs(p))))

csz = -(T * tz + cna * az + ((U2 * A2 * bz) * (p / Abs(p)))) + cw

NOTE: This section of the code differs from the original H&B code. The H&B code produces errors for the case of single plane sliding with water pressure because it does not differentiate between acute and obtuse blocks. Block theory is used here to find the removable block and to determine whether the block is acute or obtuse.

```
If JPDesignation = 0 Then
    cna = cw * az - T * s - (U2 * A2 * r)
    csx = -(T * tx + cna * ax + (U2 * A2 * bx))
    csy = -(T * ty + cna * ay + (U2 * A2 * by))
    csz = -(T * tz + cna * az + (U2 * A2 * bz)) + cw
End If
```

```
If JPDesignation = 1 Then
      cna = cw * az - T * s + (U2 * A2 * r)
      csx = -(T * tx + cna * ax - (U2 * A2 * bx))
      csy = -(T * ty + cna * ay - (U2 * A2 * by))
      csz = -(T * tz + cna * az - (U2 * A2 * bz)) + cw
End If

      csa = Sqr((csx ^ 2) + (csy ^ 2) + (csz ^ 2))  'driving force
      cqa = (cna - U1 * A1) * Tan(phi1) + c1 * A1 + SF ' resisting force

      If csa <= 0 Then
       message1 = "Driving force is upward"
       message2 = "or equal to 0!"
      Else
       fs = cqa / csa
      End If

      If fs < 0 Then
       fs = 0
      End If

   End If
```

If N1<0 and N2>0, contact is maintained on plane 2 only and the factor of safety is calculated as follows.

```
    If N1 < 0 And N2 > 0 Then
```

From H&B:

----

cnb = cw * bz - T * v - E * ve - cv * v5 - u1 * A1 * r

csx = -(T * tx + E * ex + cnb * bx + cv * f5x + u1 * A1 * ax)

csy = -(T * ty + E * ey + cnb * By + cv * f5y + u1 * A1 * ay)

csz = -(T * tz + E * ez + cnb * bz + cv * f5z + u1 * A1 * az) + cw

csa = Sqr(csx ^ 2 + csy ^ 2 + csz ^ 2)

cqa = (cnb - u2 * A2) * Tan(phi2) + c2 * A2

All variables have same meaning as in H&B.

```
        Dim cnb, cs, cq As Single

        sliding_mode = 2
```

OLD CODE

cnb = cw * bz - T * v - ((U1 * A1 * r) * (p / Abs(p)))

csx = -(T * tx + cnb * bx + ((U1 * A1 * ax) * (p / Abs(p))))

csy = -(T * ty + cnb * by + ((U1 * A1 * ay) * (p / Abs(p))))

csz = -(T * tz + cnb * bz + ((U1 * A1 * az) * (p / Abs(p)))) + cw

```
If JPDesignation = 0 Then

        cnb = cw * bz - T * v - (U1 * A1 * r)

        csx = -(T * tx + cnb * bx + (U1 * A1 * ax))
```

```
        csy = -(T * ty + cnb * by + (U1 * A1 * ay))
        csz = -(T * tz + cnb * bz + (U1 * A1 * az)) + cw
End If
If JPDesignation = 2 Then
        cnb = cw * bz - T * v + (U1 * A1 * r)
        csx = -(T * tx + cnb * bx - (U1 * A1 * ax))
        csy = -(T * ty + cnb * by - (U1 * A1 * ay))
        csz = -(T * tz + cnb * bz - (U1 * A1 * az)) + cw
End If

        csa = Sqr(csx ^ 2 + csy ^ 2 + csz ^ 2)
        cqa = (cnb - U2 * A2) * Tan(phi2) + c2 * A2 + SF

        If csa <= 0 Then
         message1 = "Driving force is upward"
         message2 = "or equal to 0!"
        Else
         fs = cqa / csa
        End If

        If fs < 0 Then
         fs = 0
        End If

    End If
```

Contact on both planes.

If N1 > 0 And N2 > 0 Then

cs = nu * (cw * iz - T * w -e*wc-cv*w5) (from H&B)

```
 sliding_mode = 0

cna = cw * az - T * s - U2 * A2 * r
csx = -(T * tx + cna * ax + U2 * A2 * bx)
csy = -(T * ty + cna * ay + U2 * A2 * by)
csz = -(T * tz + cna * az + U2 * A2 * bz) + cw

 cs = nu * (cw * iz - T * w)
 cq = N1 * Tan(phi1) + N2 * Tan(phi2) + c1 * A1 + c2 * A2 + SF

 If cs <= 0 Then
   message1 = "Driving force is upward"
   message2 = "or equal to 0!"
 Else
   fs = cq / cs
 End If

 If fs < 0 Then
  fs = 0
 End If

End If
```

Report sliding mode, plunge and trend of line of intersection, and the dihedral angle in the text box, "txtinfo".

```
Dim fs2, fs5 As Single
If JPDesignation = 0 Then
txtinfo.Text = "Plunge of Line of Intersection = " & CSng(psiii) &
vbCrLf & "Trend of Line of Intersection = " & CSng(alphaii) & vbCrLf &
"Dihedral Angle = " & CSng(dihedral1) & vbCrLf & "Area of Plane 1 = " &
CSng(A1) & vbCrLf & "Area of Plane 2 = " & CSng(A2) & vbCrLf & "Volume
of Wedge = " & CSng(Vol) & vbCrLf & "Weight = " & CSng(cw) & vbCrLf &
"Effective Normal Reaction, N1' = " & CSng(N1) & vbCrLf & "Effective
Normal Reaction, N2' = " & CSng(N2) & vbCrLf & "BP 0011 is the removable
block." & vbCrLf & "JP 00 is the removable joint pyramid."
End If
If JPDesignation = 1 Then
txtinfo.Text = "Plunge of Line of Intersection = " & CSng(psiii) &
vbCrLf & "Trend of Line of Intersection = " & CSng(alphaii) & vbCrLf &
"Dihedral Angle = " & CSng(dihedral1) & vbCrLf & "Area of Plane 1 = " &
CSng(A1) & vbCrLf & "Area of Plane 2 = " & CSng(A2) & vbCrLf & "Volume
of Wedge = " & CSng(Vol) & vbCrLf & "Weight = " & CSng(cw) & vbCrLf &
"Effective Normal Reaction, N1' = " & CSng(N1) & vbCrLf & "Effective
Normal Reaction, N2' = " & CSng(N2) & vbCrLf & "BP 0111 is the removable
wedge." & vbCrLf & "JP 01 is the removable joint pyramid."
End If
If JPDesignation = 2 Then
txtinfo.Text = "Plunge of Line of Intersection = " & CSng(psiii) &
vbCrLf & "Trend of Line of Intersection = " & CSng(alphaii) & vbCrLf &
```

```
"Dihedral Angle = " & CSng(dihedral1) & vbCrLf & "Area of Plane 1 = " &
CSng(A1) & vbCrLf & "Area of Plane 2 = " & CSng(A2) & vbCrLf & "Volume
of Wedge = " & CSng(Vol) & vbCrLf & "Weight = " & CSng(cw) & vbCrLf &
"Effective Normal Reaction, N1' = " & CSng(N1) & vbCrLf & "Effective
Normal Reaction, N2' = " & CSng(N2) & vbCrLf & "BP 1011 is the removable
wedge." & vbCrLf & "JP 10 is the removable joint pyramid."
End If

fs2 = Format(fs, "0.00")
fs5 = Format(fs, "0.00000")
```

Display factor of safety or error messages.

```
    If message1 = "" Then
      If sliding_mode = 0 Then
      Text1.Text = "Factor of Safety = " & CSng(fs2) & " (" & CSng(fs5)
& ")"
      Text2.Text = "Double Plane Sliding"
      ent = ""
      End If
      If sliding_mode = 1 Then
      Text1.Text = "Factor of Safety = " & CSng(fs2) & " (" & CSng(fs5)
& ")"
      Text2.Text = "Single Plane Sliding on Plane 1"
      ent = ""
      End If
      If sliding_mode = 2 Then
```

```
    Text1.Text = "Factor of Safety = " & CSng(fs2) & " (" & CSng(fs5)
& ")"
    Text2.Text = "Single Plane Sliding on Plane 2"
    ent = ""
    End If
  Else
    Text2.Text = message1
    Text1.Text = message2
  End If
  Exit Sub

200 Text1.Text = ent
  Text2.Text = ""
  Exit Sub

300 Text1.Text = "wrong data entry"
  Text2.Text = ""
  Exit Sub

End Sub
```

PART VIII

ALGORITHMS AND CODE - *RockSlip*

ALGORITHMS AND CODE - *RockSlip*

8.1 Geometry

Several assumptions (q3 = q2, q4 = q1) are made regarding the geometry of the rock block in *RockSlip*. These assumptions result in the cross-section of the block being a parallelogram. Gaussian Numerical Integration is used to calculate the volume of the block which is used to obtain the total weight of the block.

8.1.1 Program Code

Read parameters from text boxes. These parameters will be input in fOutcrop form.

```
Dim rho, q1, q3, q2, q4, wf, phip As Single
rho = PI / 180
q1 = Tan(OD * rho) * Cos(Abs(ODD - TR) * rho)
q1 = Atn(Abs(q1)) '(Fig 1b)
q2 = PL * rho  '(Fig 1b)
q3 = q2 '(in current version of program, Fig 1b )
q4 = q1 '(in current version of program, Fig 1b)
phip = phi * rho
wf = wf0 / 100 'drainage impedance in decimal form
```

Determination of the lowest point (xlow, ylow) of true section.

```
Dim ylow, xlow As Single
```

```
Dim numi As Integer
ylow = YT(1)
xlow = XT(1)
For numi = 2 To numpoint
    If ylow < YT(numi) Then
       ylow = YT(numi)
       xlow = XT(numi)
    End If
Next numi
```

Determination of some geometry parameters. Refer to variables diagram 1(b) for fl, hs, hc. Fd1 is the slope of line fk (Fig 1a).

```
Dim fd1, fd2, fl, hs, hc, q5 As Single
  fd1 = (YT(numpoint) - YT(1)) / (XT(numpoint) - XT(1))
  fd2 = YT(1) - fd1 * XT(1)
  fl = fd1 * xlow + fd2
  fl = (ylow - fl) / Cos(3.14159 / 2 - q4 + q2)
  hs = fl * Sin(q4) + sl * Sin(q3)
  hc = fl * Cos(q4) + sl * Cos(q3)
  hc = hc - hs / Tan(q2)
  hc = hc / (1 / Tan(q1) - 1 / Tan(q2))
  q5 = 3.14159 / 2 - q2 + q3
```

Refer to variables diagram 1(b) for L0, h0, L1, L3.

```
Dim L0, h0, L1, L3, LQ, rn, rt As Single
  Dim Msg As String
```

```
L0 = fl * Sin(q4 - q2)

h0 = hc * Sin(q1 - q2) / Sin(q1)

L1 = L0 * Cos(q4 - q2)

L3 = h0 / Tan(q1 - q2)

LQ = sl * Cos(q2 - q3)

rn = 0

rt = 0
```

Determination of inner section(which is parallel to true section) / variables diagram 1a.

```
Dim i, ii, XT0(250), YT0(250), x00(2), y00(2) As Single

Dim numin0 As Single
```

Checks if L1 and sl are parallel (var. diagram 1b).

```
If q2 - q3 = 0 Then  'this is assumed in present model.

    For ii = 1 To numpoint

        XT0(ii) = XT(ii)

        YT0(ii) = YT(ii)

    Next ii

    x00(1) = XT0(1)

    x00(2) = XT0(numpoint)

    y00(1) = YT0(1)

    y00(2) = YT0(numpoint)

    numin0 = numpoint

End If

If q2 - q3 = 0 Then GoTo 15
```

Between two points i & j (Fig 1a), which one is lower? note: y00(1) = i and y00(2) = j on variables diagram 1a.

```
15    If y00(1) >= y00(2) Then    'j is lower
         yin0 = y00(1)
         xin0 = x00(1)
      Else   'i is lower
         yin0 = y00(2)
         xin0 = x00(2)
      End If
```

Prepare for the calculation of block weight.

```
90  If q2 = q3 Then GoTo 110 'current assumption
```

Determination of block weight (case 2). q2=q3

The first block of code determines the length between the front and back faces of the block. Uses the equation of a plane : $z = Ax + By + C$, where z is desired length, A is coea1&2, B is coeb1&2, C is coec1&2 (coefficients). Here we solve for z (a length). This calculates the total block volume. This calculation was designed to handle the general case (q1 <> q4), using Gauss points. Gauss method is not really necessary for our assumption q1=q4.

```
110 coeb1 = (YT(1) - YT(numpoint)) / (XT(1) - XT(numpoint))
    coeb1 = coeb1 - (ylow - YT(numpoint)) / (xlow - XT(numpoint))
    coeb1 = -L3 / (xlow - XT(numpoint)) / coeb1
    coea1 = -(YT(1) - YT(numpoint)) / (XT(1) - XT(numpoint)) * coeb1
```

```
coec1 = -coea1 * XT(1) - coeb1 * YT(1)
coeb2 = (YT(1) - YT(numpoint)) / (XT(1) - XT(numpoint))
coeb2 = coeb2 - (ylow - YT(numpoint)) / (xlow - XT(numpoint))
coeb2 = -L1 / (xlow - XT(numpoint)) / coeb2
coea2 = -(YT(1) - YT(numpoint)) / (XT(1) - XT(numpoint)) * coeb2
coec2 = s1 - coea2 * XT(1) - coeb2 * YT(1)
Dim cc1, cc2, cc3 As Single
cc1 = coea2 - coea1
cc2 = coeb2 - coeb1
cc3 = coec2 - coec1
volb = 0#
y01 = (YT(numpoint) - YT(1)) / (XT(numpoint) - XT(1))
y02 = YT(1) - y01 * XT(1)
 For gau = 1 To numpoint - 1
   a1 = XT(gau)
   b1 = XT(gau + 1)
   s1 = YT(gau)
   t1 = YT(gau + 1)
```

Uses numerical integration to calculate the volume of rock.

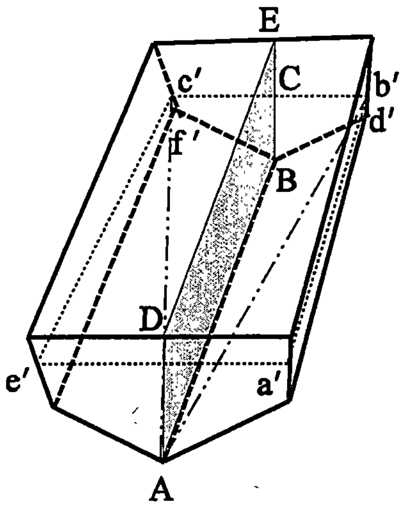
```
   Call gausb(a1, b1, s1, t1, y01, y02, cc1, cc2, cc3)
   volb = volb + gausb(a1, b1, s1, t1, y01, y02, cc1, cc2, cc3)
Next gau
```

volb is the volume; gammab is the unit weight of the rock.

```
120 volb = volb * gammab
```

volb is now a weight.

8.2 Water Force



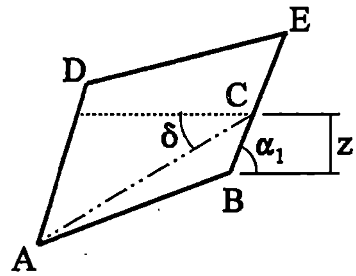


Figure 8.1 Folded rock geometry modeled as a prism.

Three cases are considered:

a. Drained case,

b. Undrained case and

c. Partially Drained case.

8.2.1 Drained case

In the Drained case, we assume that the water level is equivalent to plane Ab'c'(See Fig. 8.1). Using the same method used above, we can get the magnitude of the total water force $\boldsymbol{F}^D$ as following:

$$|F^D| = V_{Ab'c'f'Bd'} \times \gamma \times \sin(\alpha_1)/\sin(\alpha_1 - \delta) \qquad \textbf{(8.1)}$$

where $V_{Ab'c'f'Bd'}$ is the volume of block Ab'c'f'Bd', γ is the unit weight of water.

The calculation of the volume of the block is complicated and requires the use of the three point Gaussian Numerical Integration Method. For example, set the origin at point E (point E is in the vertical plane going through line AB), axis y perpendicular to line AB and downward, axis x horizontal and axis z parallel to line AB. Then we can get the equations of plane Ab'c' and plane Bd'b'c'f':

plane Ab'c': $z_1 = A_1x + B_1y + C_1$

plane Bd'b'c'f': $z_2 = A_2x + B_2y + C_2$

Let Ω denote the projection district of plane Bd'b'c'f' at plane $z = 0$, then the volume of block Ab'c' can be calculated as follows:

$$V_{ab'c'} = \iint (z_1 - z_2)dxdy \qquad (x, y \in \Omega) \qquad \textbf{(8.2)}$$

We can easily convert the above equation into the following form:

$$V_{ab'c'} = \int_{-1}^{1} d\xi \int_{-1}^{1} f(\xi, \eta)\, d\eta \qquad \textbf{(8.3)}$$

then we have

$$V_{ab'c'} = \sum_{i=1}^{n} H_i \sum_{i=1}^{n} H_j f(\xi_j \eta_i) \qquad \textbf{(8.4)}$$

Here ξ_j and η_I are Gauss points, and H_i and H_j are Gauss coefficients. If three Gauss points are applied, the three Gauss point are -0.774596692, 0, 0.774596692, the Gauss coefficients corresponding to the Gauss points are 0.5555555559, 0.8888888889, 0.5555555559.

The direction of F^D is perpendicular to plane Ab'c'.

8.2.2 Undrained Case

In the Undrained case, the water plane is a'b'c'e'. It is a horizontal plane. The method used to calculate the water force is the same as that used in wedge failure. One difference is that the Gaussian Numerical Integration Method is adopted to calculate the volume of block a'b'c'e'AB in prismatic failure. Total water force F^w is

$$F^w = F'' - F' \qquad \textbf{(8.5)}$$

the meaning of F'' and F' is the same as that in wedge failure.

8.2.3 Partially Drained Case

The calculation method is the same as that used in wedge failure. Total water force **F** is

$$F = F^s + (F^w - F) \times W^f / 100 \qquad \textbf{(8.6)}$$

8.2.4 Program Code

The code used in *RockSlip* to calculate the water force is listed below. Overall, the code follows the algorithms outlined in the previous sections for calculating the water force in each case. Some differences exist in the variable names and the order in which quantities are calculated. Also, the code contains the logical operators used to distinguish between the different cases and in some instances, the different slope geometries that are possible.

Determination of maximum water level permitted.

```
Dim zwmax, zw1, yin, x12, y12 As Single
```

```
Dim sym As String
zwmax = (ylow - yin0) * Sin(q1) / Sin(q1 - q2)
If zwmax = 0 Or zw = 0 Then GoTo 90
```

At the beginning, should input zw. Determine whether data entry is wrong.

```
If zw > zwmax Or zwmax < 0 Then
  sym = Str$(Int(zwmax))
  If zwmax < 0 Then sym = "0"
  Msg = "Maximum zw permitted is " + sym + vbCrLf
  Msg = Msg + "Your input is out of range !"
  MsgBox Msg, vbOKOnly + vbCritical
  Me.Hide
  fOutcrop.Show
  With fOutcrop.txtUserInput(5)
   .SetFocus
   .SelStart = 0
   .SelLength = Len(.Text)
  End With
  Exit Sub
End If
```

Determination of the water plane level. Prepare for the calculation of water pressure.

```
zw1 = zw * Sin(q1 - q2) / Sin(q1)
```

zw1 = distance between AB & FC Fig 2b.

```
yin = ylow - zw1
```

yin = distance between DE & FC Fig 2b

```
j = 1
```

The following variable arrays are used to store the coordinates of the intersection points of the water level with the true section.

```
Dim x22(2), y22(2) As Single
```

XT0 & YT0 are the coordinates of the endpoints of the line segments in the true profile.

```
For i = 1 To numin0 - 1
    If XT0(i) - XT0(i + 1) = 0 Then
        x12 = XT0(i)
        y12 = yin
    Else
```

dd = slope of each plane in the true section.

```
dd = (YT0(i + 1) - YT0(i)) / (XT0(i + 1) - XT0(i))
```

Solve linear equation for ee : y = dd*x + ee.

```
        ee = YT0(i) - dd * XT0(i)
        If dd = 0 Then GoTo 25
        x12 = (yin - ee) / dd
        y12 = yin
```

```
End If
```

Is (x12, y12), as calculated in the previous block, a real intersection point? If so, store the coordinates of the intersection as (x22(j), y22(j)).

```
If j = 2 Then GoTo 20
```

The next if then statement checks to see if plane in the true section is vertical.

```
If XT0(i) - XT0(i + 1) = 0 Then
```

The next 2 if then statements check the position of point y12.

```
    If y12 >= YT0(i) And y12 < YT0(i + 1) Then
        x22(j) = x12
        y22(j) = y12
        reco(j) = i
        j = 2
    End If
    If y12 = YT0(i + 1) Then
        x22(j) = x12
        y22(j) = y12
        reco(j) = i + 1
        j = 2
    End If
End If
```

The next 2 if then statements check the position of point x12.

```
If x12 <= XT0(i) And x12 > XT0(i + 1) Then
   If y12 >= YT0(i) And y12 < YT0(i + 1) Then
   x22(j) = x12
   y22(j) = y12
   reco(j) = i
   j = 2
   End If
End If
If x12 = XT0(i + 1) And y12 = YT0(i + 1) Then
   x22(j) = x12
   y22(j) = y12
   reco(j) = i + 1
   j = 2
End If
GoTo 25 ' This goto statement restarts the loop
```

This block is identical to the previous block except it determines the second intersection point.

```
20  If XT0(i) - XT0(i + 1) = 0 Then
       If y12 = YT0(i) Then
           x22(j) = x12
           y22(j) = y12
           reco(j) = i
       End If
       If y12 < YT0(i) And y12 >= YT0(i + 1) Then
           x22(j) = x12
```

```
            y22(j) = y12
            reco(j) = i + 1
         End If
      End If
      If x12 < XT0(i) And x12 >= XT0(i + 1) Then
         If y12 < YT0(i) And y12 >= YT0(i + 1) Then
         x22(j) = x12
         y22(j) = y12
         reco(j) = i + 1
         End If
      End If
      If x12 = XT0(i) And y12 = YT0(i) Then
         x22(j) = x12
         y22(j) = y12
         reco(j) = i
      End If
25   Next i
```

Calculate the total number of points along the inner water section.

```
Dim numinw As Integer
Dim XT1(250), YT1(250) As Single
Dim LW1, LW2 As Single
numinw = reco(2) - reco(1) + 1
```

Get coordinates of true inner water section.

```
   For i = 2 To numinw - 1
```

```
        k = reco(1) + i - 1
        XT1(i) = XT0(k)
        YT1(i) = YT0(k)
    Next i
    XT1(1) = x22(1)
    XT1(numinw) = x22(2)
    YT1(1) = yin
    YT1(numinw) = yin
```

Determination of some parameters related to water level (see variables diagram 1 b).

```
    LW1 = zw * Cos(q1 - q2) / Sin(q1)
    LW2 = (hs - hc) / Sin(q2) + LW1
```

Determine water pressure(unfrozen--related to 0 of outlet frozen level).

```
  Dim gau As Integer
    Dim volw, Y0, a1, b1, s1, t1 As Single
    Dim coeb1, coeb2, coec1, coec2, coeb, coec As Single
    Dim coea1, coea2 As Single
30  volw = 0
    Y0 = YT1(1)
    For gau = 1 To numinw - 1 ' gau is a counter
```

a1, b1, s1, t1 are given values of the coordinates.

```
      a1 = XT1(gau)
      b1 = XT1(gau + 1)
      s1 = YT1(gau)
```

```
t1 = YT1(gau + 1)
coeb1 = LW2 / (ylow - YT1(1))
coec1 = -coeb1 * YT1(1)
coeb2 = LW1 / (ylow - YT1(1))
coec2 = -coeb2 * YT1(1)
coeb = coeb1 - coeb2
coec = coec1 - coec2
Call gauss(a1, b1, s1, t1, Y0, coeb, coec)
```

Uses numerical integration to calculate the volume of water (area abc in fig 2a). First calculate coordinates of intersections of wedge planes with water plane for summer case. Four points are calculated for each sliding plane. x & y coordinates (XT1(i), YT1(i)) are determined for each point. The z coordinate (unnamed) is calculated so the point lies in the plane.

```
volw = volw + gauss(a1, b1, s1, t1, Y0, coeb, coec)
Next gau
Dim delta1, LL, LW As Single 'see fig. 2
delta1 = (zw / Tan(q1) + (hs - hc) / Tan(q2))
delta1 = (hs - hc + zw) / delta1
delta1 = Atn(delta1)
volw = volw * Sin(q1) / Sin(q1 - q2) * gammaw
rn = -volw * Cos(delta1 - q2)
rt = volw * Sin(delta1 - q2)
```

Consider winter case. Outlet frozen level changes from 0-100%.

```
LL = Sqr((XT1(1) - XT1(numinw)) ^ 2 + (YT1(1) - YT1(numinw)) ^ 2)
rn = rn - zw * wf * LL * sl * gammaw / 2
```

Note: due to the assumption that the water pressure head is related to the length zw in both case a and c the assumption that follows is that there is a maximum drainage impedance assumed, which is equal to the following: Max Drainage imped. = zw / (zw + (hs - hc)) x 100%.

8.3 Factor of Safety

The factor of safety is calculated as the ratio of resisting to driving forces. The following code shows how cohesion is incorporated into the calculation of the resisting forces. Several checks are performed on the resisting and driving forces to ensure their validity.

8.3.1 Program Code

Calculates normal and driving forces.

```
rn = volb * Cos(q2) + rn 'normal component of weight
rt = volb * Sin(q2) + rt 'driving component of weight
```

Checks to see if calculated driving force is valid.

```
If rt <= 0 Then
  Msg = "Driving force is upward or 0 !" + vbCrLf
```

Driving force points up along line of intersection (very safe).

```
    Msg = Msg + "Safety Factor is set to 999999."
    MsgBox Msg
    FS1C = 999999
    Exit Sub
  End If
```

Checks to see if calculated normal force is valid.

```
  If rn < 0 Then
  Msg = "Normal force is negative" '(no friction:very unsafe)
  MsgBox Msg
  FS1C = 0
  Exit Sub
  End If
Dim cohesion As Single
```

Calculates cohesion force on all planes and sums the results.

```
  cohesion = 0
  For i = 1 To numplanes
  cohesion = cohesion + sl * LT(i) * cohe
```

This is the cohesion force.

```
  Next i
```

rn = normal force

FS1 is equal to FS in eq 24 (Mauldon & Ureta) (assumes zero cohesion). We multiply FS1 by (Rn/(Rt tan delta)) to obtain FS in eq 23 (M&U). Then add cohesion to the resistance. FS1C incorporates cohesion.

```
FS1C = (rn * FS1 / Tan(PI / 2 - q2) + cohesion) / rt
If FS1C < 0 Then
FS1C = 0
End If
```

PART IX

CONCLUSIONS

CONCLUSIONS

A family of three computer programs, entitled *ROCKSLIP*, has been developed to rapidly assess the stability of a wide variety of rock slope configurations. The user-friendly setup of each program allows the user to quickly analyze the particular slope geometry at hand. Visual Basic 5.0 Professional Edition© has been used to develop the programs. The use of this 32-bit developing environment has allowed a compact and eye-pleasing design for all the programs. All the programs are *Windows* based applications and compatible with *Windows 95/98/NT.*

Several features make these programs unique and powerful tools in the workplace. The auto-redraw function serves as a flexible and practical design tool, making it possible for professionals in the rock engineering field to perform complex studies, such as sensitivity analyses, and for students to better visualize the orientations of each physical component of the slope. An effort to better model the effects of water pressure has resulted in a parameter entitled "drainage impedance". This parameter allows the user to adjust the drainage conditions at the toe of the slope. The effects of cohesion, water pressure and friction angle are also accounted for. Rockbolt reinforcement can be added to the analysis. Number, length, orientation, tensile and shear strength and minimum embedment can all be adjusted depending on the type of rockbolt and the installation procedure used. There are some limitations to the programs. For instance, *WedgeSlip* does not allow for a tension crack to be present (this feature will be added in a later version).

The contents of this thesis have summarized the work done on this project and describe the three computer programs that have been designed. The User's Guides provide a simple introduction to each program and explain the basics involved in operating and obtaining results from the programs. The TDOT Slopes History (Appendix B) demonstrates the need for further planning and development of methods to help prevent future slope failures throughout Tennessee (especially Eastern Tennessee). The *ROCKSLIP* family of programs marks a significant stride in the progression of analysis techniques for rock slopes.

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APPENDICES

APPENDIX A

THE *ROCKSLIP*™ WORKBOOK

A Companion Work for the *ROCKSLIP*™ Software Package

Prepared by the Institute for Geotechnology,
The University of Tennessee, Knoxville

June 1999

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

1.1 Program Development History

The original impetus behind this project was to implement a new rock slope stability analysis method to analyze slopes consisting of folded rock geometries. Since the failure surface is essentially a series of *m* planes (m>2), limiting equilibrium analysis yields an indeterminate answer for these slopes. A method based on potential energy was developed for stability analysis in such cases. For a detailed explanation of this method, please see Mauldon and Ureta (1996) and Mauldon, Arwood and Pionke (1998). This analysis technique was adapted into a computer program entitled *RockSlip*. As time progressed, additional programs to analyze other basic rock slope geometries were developed. *WedgeSlip* and *PlaneSlip* were the results of this effort. The set of three programs is referred to as the *ROCKSLIP* package. The current version of the programs is version 1.3.

1.2 Program Features

- **Windows Based** - All three programs are *Windows* based and are compatible with *Windows 95/98/NT* operating systems.
- **Units of Measurement** - All three programs allow for the use of two different measuring systems, fps (English) and SI (Metric). *PlaneSlip* and *WedgeSlip* automatically convert between the two.
- **Auto-Redraw** - Included in *PlaneSlip* and *WedgeSlip*. The *auto-redraw* function

enables the user to change key parameters and see, in "real-time", how these changes affect the slope's stability.

- **Rockbolts** - The effects of rock reinforcement are included in *PlaneSlip* and *WedgeSlip*. Parameters such as number, orientation, tensile and shear capacity, minimum embedment length and horizontal spacing can be defined for the rock reinforcement.
- **Examples** - Included in *PlaneSlip* and *WedgeSlip*. Several example problems are included under the pull-down menu "Data", which are based on published results.
- **Water Level** - Included in *PlaneSlip* and *RockSlip*. The height of water in the tension crack controls the magnitude of water pressure acting on the slope.
- **Drainage Impedance** - Included in *PlaneSlip* and *RockSlip*. A parameter entitled "drainage impedance" has been incorporated into the program, which allows the user to change the pressure distribution behind the slope by varying the drainage conditions along the sliding plane and at the toe of the slope.
- **Tension Crack Angle** - Included in *PlaneSlip*. The angle of the tension crack can also be adjusted. This is a feature that has not been included in much of the previous work on rock slopes (e.g., Hoek & Bray, 1981).
- **Graphical Output** - *WedgeSlip* displays a choice of several diagrams (including upper and lower hemisphere stereographic projections, cross section and variables diagram) which aid the user in grasping the physical scenario.
- **Water Pressure** - Included in *WedgeSlip*. The effects of water pressure on wedge stability are also accounted for with the average water pressure parameters.

- **Y2K Compliant** - *PlaneSlip, WedgeSlip* and *RockSlip* include no reference to date and are therefore fully Y2K compliant.

1.3 Assumptions

The following assumptions are made in all three programs:

- All forces are assumed to act through the centroid of the sliding mass. This implies that there are no moments created by the forces acting on the block. The error introduced by ignoring the moments is negligible (Hoek & Bray, 1981).
- The shear strength of the sliding plane is defined by the Mohr-Coulomb criterion:

$$\tau_f = c + \sigma'_f \tan\phi \tag{1}$$

where τ_f = shear stress at failure, c = cohesion, σ'_f = effective normal stress at failure, and ϕ = friction angle.

- In *PlaneSlip* and *WedgeSlip*, the block is treated as a rigid body. In *RockSlip*, the block itself is assumed to be undeformable, deformation occurring only at the contact faces.
- The block is acted upon by an active resultant force ***R***, which includes self weight, and may include other forces, such as water forces and rockbolt forces.
- The frictional shear stresses are assumed to act parallel to the direction of sliding only (Hoek and Bray, 1981; Chan and Einstein, 1981). This is a standard assumption in limiting equilibrium analyses of slopes.

1.4 Disclaimer

The authors disclaim any responsibility for the correctness of the data generated by the *PlaneSlip* package, or for the consequences resulting from the use thereof. Any use or misuse of this package is the sole responsibility of the user.

CHAPTER 2. *PlaneSlip* EXAMPLES

2.1 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. Thus, one must define an index which describes the relationship between driving and resisting forces for each geometric and mechanical situation in a rock slope. This is traditionally done using an index called the *Factor of Safety*, defined as the ratio of the total resisting force to the total driving force. For plane sliding including water pressure and rock reinforcement, the equation for calculating the FS is as follows (Hoek & Bray, 1981). See Table A.1 for definition of variables.

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p + N_b F_b \cos\beta)\tan\phi + (N_b S_b / S_h)}{W\sin\psi_p + V\cos\psi_p - N_b F_b \sin\beta} \tag{2}$$

Table A.1. Definition of Variables (*PlaneSlip*)

Variable	Description
FS	Factor of safety
c	Cohesion
A	Area of failure surface
W	Weight of sliding mass
ψ_p	Dip of failure plane
U	Uplift water force on failure plane

Variable	Description
V	Water force on tension crack
ϕ	Friction angle
N_b	Number of rockbolts with embedment length greater than the minimum.
F_b	Tensile force in rockbolts
β	The angle the bolts make with the normal to failure plane
S_b	Shear strength of rockbolts
S_h	Horizontal spacing of rockbolts

2.2 Additional Assumptions

The following assumptions are unique to *PlaneSlip*:

- The sliding surface and the tension crack strike parallel to the slope surface.
- Water enters the sliding surface along the base of the tension crack and seeps along the sliding surface, escaping at atmospheric pressure where the sliding surface daylights in the slope face. This is the case when there is no drainage impedance at the toe of the slope. If drainage is impeded then the water pressure distribution on the sliding surface is modified according to the amount of impedance.
- A slice of unit thickness is considered and it is assumed that release surfaces are present, so that there is no resistance to sliding at the lateral boundaries of the failure.

2.3 Worked Examples

Example PS - 1 Introduction to Features and Display Options

Source: Limestone Quarry in Alabama (unpublished)

Orientation Data:

<u>Discontinuity Type</u>	
Slope Face Dip	54°
Top Face Dip	0°
Sliding Plane Dip	30°
Tension Crack Dip	90°
Slope Geometry:	
Face Height	10 m
Upper Slope Length	2 m
Mechanical Parameters:	
Friction Angle	30°
Cohesion	0 kPa
Water Level	0 m
Unit Weight	27 kN/m^3
Drainage Impedance	0 %
Output:	
Factor of Safety	1
Max. Water Level	4.65 m

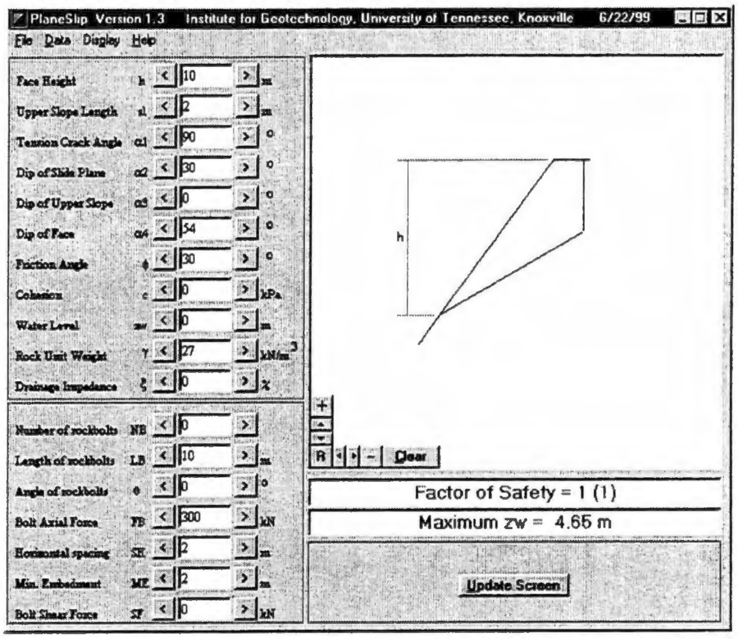

Figure PS - 1a

Discussion:

This introductory example introduces the user to some of the major plotting and calculation options available in *PlaneSlip*. To access Example 1 go to **Data ⇒ Examples ⇒ Example 1 (Limestone Quarry)**. When the example first appears the variables diagram will be in the picture box. To be able to view the slope cross-section the user must turn off the variables diagram. To do this go to **Display ⇒ Variables Diagram** and click. Note the picture controls in the lower left hand corner of the picture box. The cross-section should be small and off-center when it first appears. Increase the size by clicking on the "+" button and adjust its position with the horizontal and vertical scroll bars.

PlaneSlip handles the calculation of **water pressure** for stability calculations in a different manner than in *WedgeSlip*. The parameter that controls water pressure in *PlaneSlip* is the **water level** in the tension crack. Try raising the water level to 2 meters. Notice the decrease in the factor of safety. Now imagine that the slope undergoes an episode of freezing temperatures. The drainage may be impeded due to water which cannot exit from the toe of the slope because it has frozen. *PlaneSlip* can account for not only this occurrence, but for any existing condition which may worsen drainage conditions, with a parameter entitled **drainage impedance**. Try raising the drainage impedance to 50%. The screen should look like Figure PS - 1b and the factor of safety should drop from 1 to 0.56.

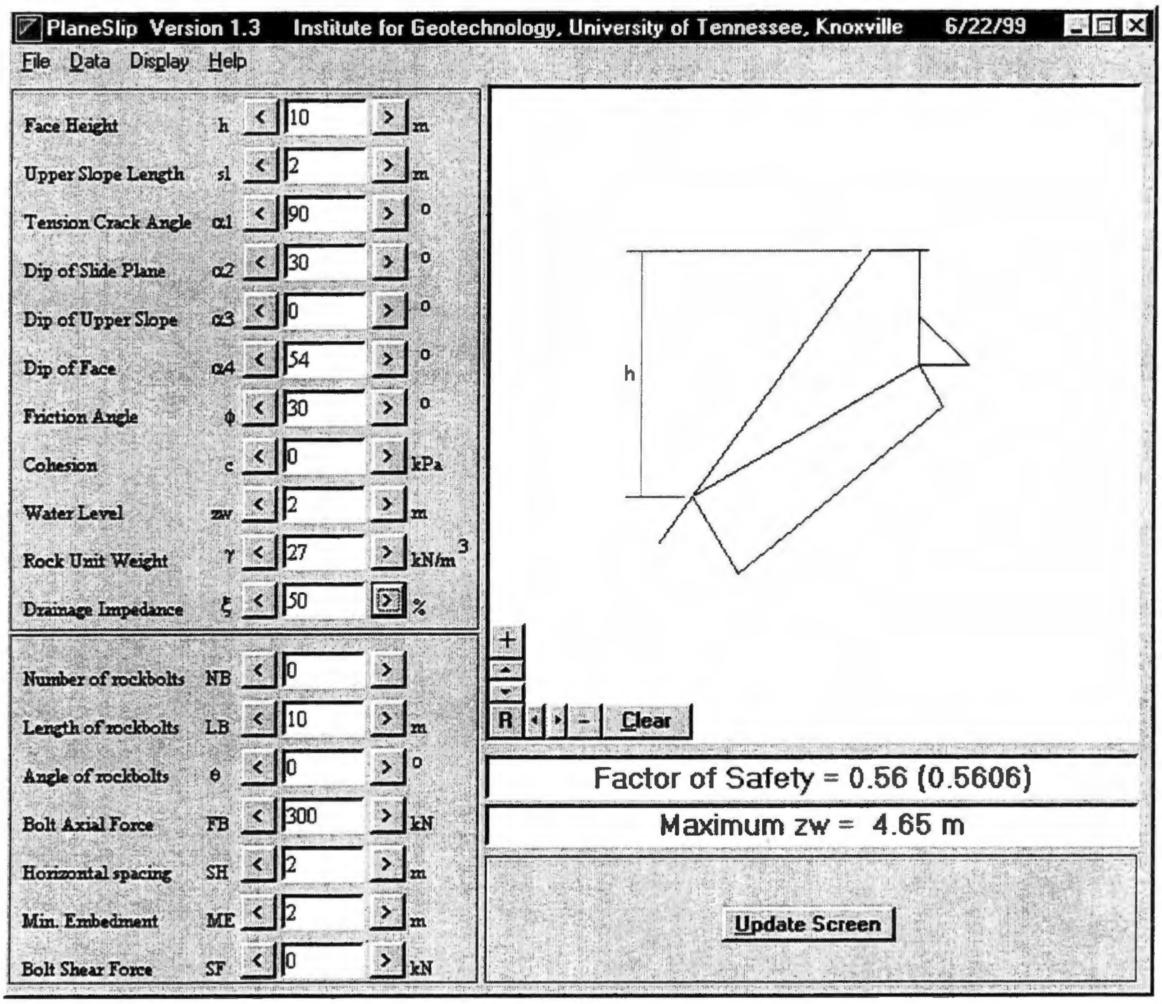

Figure PS - 1b

Now examine the effects of **rock reinforcement.** To add rockbolts to the slope simply adjust the number of rockbolts (located directly below the drainage impedance input). Note the increase in the factor of safety. Try shortening the bolts. What happens to the cross-section diagram when a rockbolt ceases to meet the minimum embedment requirement? What happens to the factor of safety? Another important aspect of rock reinforcement is the angle at which the rockbolts are installed. Notice how the factor of safety responds to changes in the **rockbolt angle.** The **bolt axial force** represents the total force transmitted to the sliding plane by the rockbolt. Depending on what is required to generate the force in the bolt (i.e., is it motion in the slope or is the bolt post-tensioned?), the force can be chosen from a list of typical rockbolt parameters. Simply go to **Data ⇒ Typical Rockbolt Parameters** and choose the value of axial force accordingly. **Horizontal spacing** is another aspect of rockbolts that PlaneSlip accounts for. If horizontal spacing increases the factor of safety should decrease and vice versa. Finally, one may include some **shear resistance** or "dowel effect" for the rockbolts.

Example PS - 2 Water Pressure and Rock Reinforcement

Source: TRB Special Report 247

Orientation Data:	
<u>Discontinuity Type</u>	
Slope Face Dip	70°
Top Face Dip	11°
Sliding Plane Dip	30°
Tension Crack Dip	90°
Slope Geometry:	
Face Height	30 m
Upper Slope Length	15 m
Mechanical Parameters:	
Friction Angle	25°
Cohesion	96 kPa
Water Level	9 m
Unit Weight	25 kN/m^3
Drainage Impedance	0 %
Output:	
Factor of Safety	1.13
Max.Water Level	18.06 m

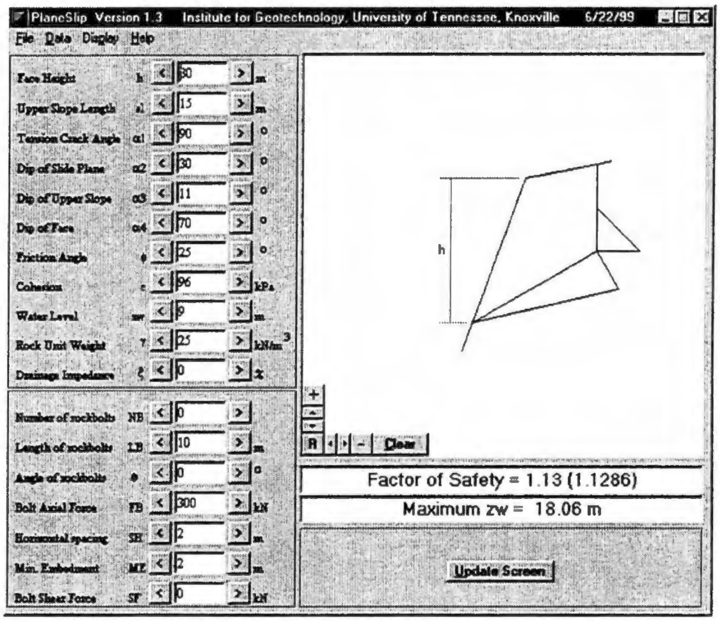

Figure PS - 2a

Discussion:

This example is designed to help the user better understand the rock reinforcement and water pressure functions in *PlaneSlip* and also perform a small sensitivity analysis. To access Example 2 go to **Data ⇒ Examples ⇒ Example 2 (TRB Special Report 247, 1996).** Turn off the variables diagram and adjust the size and position of the cross-section as desired. Now your screen should be similar to the one pictured in Figure PS - 2a.

The calculated factor of safety should be 1.13 for the tension crack approximately half-filled with water. This factor of safety would be considered unsafe as regards the long-term performance of the slope. Therefore, stabilization measures should be taken for this slope.

It is useful at this point to perform sensitivity analyses which can help indicate which stabilization method is optimal. For example, if the option of stabilization through increasing slope drainage is of interest, one may want to examine the sensitivity of the slope to changes in the water level in the tension crack. For a dry slope (water level equal to 0 m), *PlaneSlip* yields a factor of safety of 1.33. For a fully saturated slope (water level equal to 18 m), *PlaneSlip* yields a factor of safety of 0.83. Even if measures were taken to promote full drainage of the slope at all times, the factor of safety would be 1.33, which is marginal for design purposes. Thus, from this sensitivity analysis, one can determine that other stabilization methods need to be investigated.

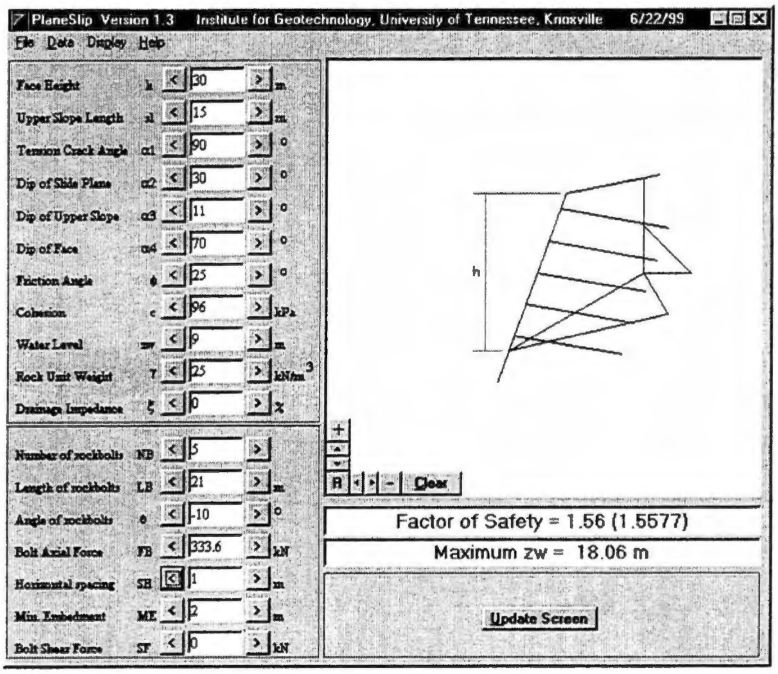

Figure PS - 2b

Rock reinforcement through the use of rockbolts or anchors is the next stabilization option that needs to be examined. Begin with the initial slope conditions (tension crack half-filled with water). Add one rockbolt. Use $\theta = -10°$ to correspond with the angle of 50° (defined differently) in the TRB report. Note that this is not the optimal orientation but rather a practical decision based on installation and grouting procedures. Increase the length of the rockbolt to at least 18 meters to meet the minimum embedment requirement. Change the horizontal spacing to 1 m (this is so the example results will match with the TRB analysis, which analyzes the reinforcement per unit length of the slope). Now increase the bolt axial force till the factor of safety rises above 1.5 (typical required factor of safety for slope design). Based on the above information the bolt axial force required for this scenario is approximately 1500 kN. To make direct changes in input simply delete the current value, type in the new value and click on "Update Screen". Note that this value is for one rockbolt spaced at a unit length of 1m. Different combinations of spacing and bolt force could be used to obtain the design factor of safety. Using a typical post-tension value of 75 kips (333 kN), five bolts would be needed per 1 meter of slope length (Figure PS - 2b). One way to enter this value for bolt force is to select it from the **Data ⇒ Typical Rockbolt Parameters ⇒ Rockbolt Axial Force (based on post-tension stress)** submenu. Regardless of the combination used, one should perform the same sensitivity analysis as before with the reinforced slope to verify that it will be stable under extreme conditions. For a fully saturated slope with reinforcement, the factor of safety is 1.08. This is an acceptable factor of safety for this extreme condition.

Example PS - 3 Pull-down Menus; Saving Bitmaps

Source: *Rock Slope Engineering* by Hoek & Bray, 1981

Orientation Data:	
<u>Discontinuity Type</u>	
Slope Face Dip	60°
Top Face Dip	0°
Sliding Plane Dip	30°
Tension Crack Dip	90°
Slope Geometry:	
Face Height	100 ft
Upper Slope Length	29 ft
Mechanical Parameters:	
Friction Angle	30°
Cohesion	1000 psf
Water Level	0 ft
Unit Weight	160 pcf
Drainage Impedance	0 %
Output:	
Factor of Safety	1.35
Max. Water Level	49.92 ft

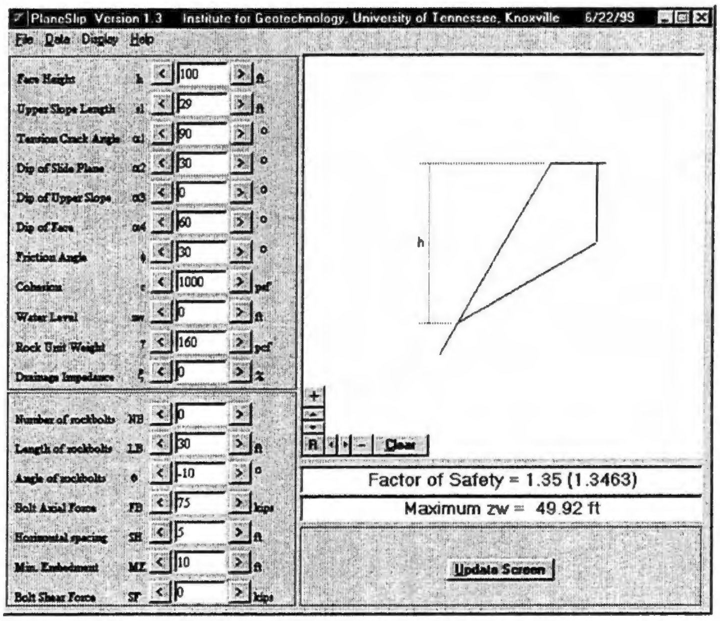

Figure PS - 3a

Discussion:

To access Example 3 go to **Data ⇒ Examples ⇒ Example 3 (Hoek and Bray, 1981)**. Turn off the variables diagram and adjust the size and position of the cross-section as desired. Now your screen should be similar to the one pictured in Figure PS - 3a.

This example will illustrate the use of preset values for friction angle and unit weight available in *PlaneSlip*. To access the preset values for friction angle go to **Data ⇒ Typical Ultimate Strengths, phi, degrees (c = 0)**. The values listed are taken from Franklin and Dusseault (1989). Note that there are two sections within this submenu, "Thick joint fillings" and "Rock joints". There are six presets under "Thick joint fillings" and nine under "Rock joints". The first six values are for cases where the infilling substance in the joint or sliding plane provides the primary frictional resistance to sliding. The last nine are cases where there is little or no filling and the discontinuity contact surfaces provide the majority of the frictional resistance. There is a range of values provided in the submenu for each case. The median value is inserted in the "Friction Angle" input box when the preset is clicked on. However, the range of values should provide a framework within which good engineering judgement can allow for adjustment of the median value to provide a more accurate estimate of the friction angle from case to case.

To access the preset values for unit weight go to **Data ⇒ Typical Unit Weights**

(kN/m^3). The values listed are taken from Goodman (1989). Once again, these values are not written in stone and can be adjusted based on available test data and engineering judgement. They are listed as *typical* values for the particular rock types.

Another interesting feature in PlaneSlip is the ability to save the cross-sectional diagram as a bitmap. First, position the cross-section in the picture box as desired. This is done using the "+" and "-" buttons to zoom in and out and the horizontal and vertical scroll bars to adjust left and right position (See Example PS - 1). Then go to **Display ⇒ Save As Bitmap....** A dialog box should appear asking for a location and filename to save the bitmap under. Select a directory to save the bitmap in and assign it a filename. The bitmap can then be accessed and inserted into any typical word processing software (WordPerfect©, Word©). The bitmap can also be manipulated (image effects, add text) in any image processing software that will open bitmaps (Paint©, Corel® Photo House). Figure PS - 3b is an example bitmap created using the slope configuration in Example 3 with the tension crack fully filled with water.

Another way to create images using *PlaneSlip* is to capture the active screen and paste it into a document. Simply get the form you want to capture on the screen and make sure it is the active form. Then press "Alt + Print Scrn". *Windows* captures the active form. Now go to either a word processing or image editing program and use the "Paste" command. The entire form should appear as an image. An example of this process is all the introductory program screens shown at the beginning of each the *PlaneSlip* example problems.

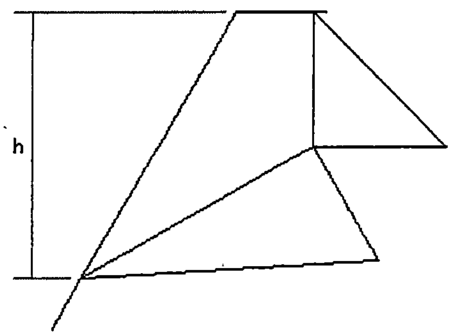

Figure PS - 3b

Example PS - 4 Bedding Plane Slides; Passive Reinforcement

Source: Saieb Haddad, TDOT Region One

Orientation Data:

<u>Discontinuity Type</u>

Slope Face	70°
Top Face	30°
Sliding Plane	30°
Tension Crack	70°
Slope Geometry:	
Face Height	20 ft
Upper Slope Length	60 ft
Mechanical Parameters:	
Friction Angle	30°
Cohesion	0 psf
Water Level	0 ft
Unit Weight	170 pcf
Drainage Impedance	0 %
Output:	
Factor of Safety	1
Max. Water Level	20 ft

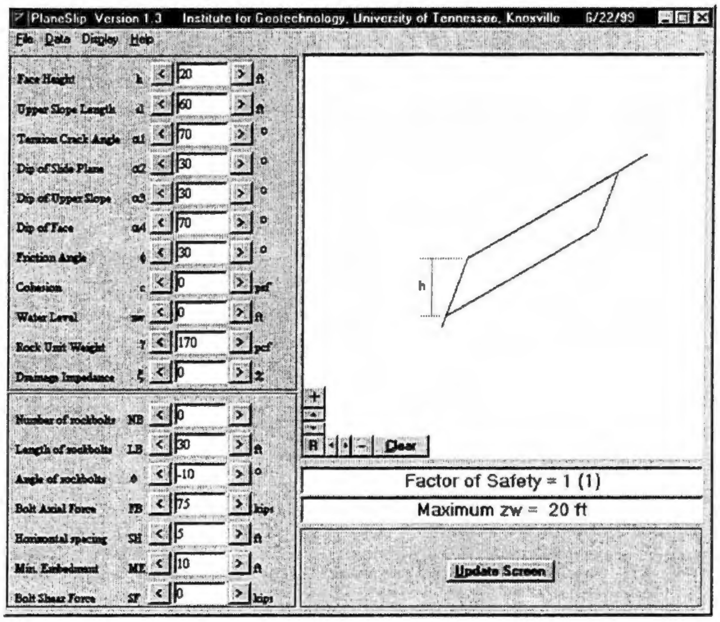

Figure PS - 4a

Discussion:

To access Example 4 go to **Data ⇒ Examples ⇒ Example 4 (Uniformly Bedded Rock)**. Turn off the variables diagram and adjust the size and position of the cross-section as desired. Now your screen should be similar to the one pictured in Figure PS - 4a.

Reinforcement for bedding plane slides such as are common is East Tennessee is usually placed through the top face rather than the slope face. Although the current version of *PlaneSlip* allows bolts to be placed only through the slope face, the program can still be used for the stability calculation.

The use of rockbolts as active reinforcement in a rock slope has already been discussed (See Example PS - 2). Now examine the use of rockbolts as passive reinforcement. There are cases, such as this configuration, where rockbolts can be used as "dowels" to hold the rock block in place. Note that if rockbolts are installed for this purpose (i.e. they are not post-tensioned) care must be taken when including them in stability calculations. It is recommended that sixty percent of the ultimate strength be used to estimate the shear resistance of the bolts. Also, this value should be entered in the "Bolt **Shear** Force" input box and not the "Bolt **Axial** Force" input box. This mixup can be avoided by using the preset values available under the pull-down menus at the top of the screen. Simply go to the **Data ⇒ Typical Rockbolt Parameters ⇒ Rockbolt Axial Force (based on 60% ultimate strength)** submenu. Three preset values can be chosen depending on the size of the bolt being used. When one of these values is selected *PlaneSlip* automatically enters the correct value for the bolt shear force and zeroes out the bolt axial force. It is not required that the preset values for shear force be used, but this is a good method to insure that the value is entered in the appropriate input box and that the axial force is reduced to zero. The latter insures that the rockbolt is truly being modeled as a "dowel", providing only shear resistance to sliding.

Try adding rockbolts as "dowels" to this example. Use the 1" nominal diameter all-thread bar preset (76.5 kips). Assuming a minimum embedment requirement of ten feet and horizontal spacing of five feet, three rockbolts are required to raise the factor of safety above 1.5. The rockbolts need to have a minimum length of 25 feet to meet the minimum embedment requirement. The rockbolts are oriented normal to the sliding plane ($\theta = \alpha_4 - \alpha_2 = 70° - 30° = 40°$). This configuration will produce an output screen similar to Figure PS - 4b. The factor of safety should equal 1.55, which is sufficient for the dry slope conditions. If the water level were to rise and fill the tension crack halfway, another bolt would be needed to raise the factor of safety above 1.5 (1.51 for this case). Thus, it is advisable to add the fourth bolt to account for the possibility of a partially saturated slope.

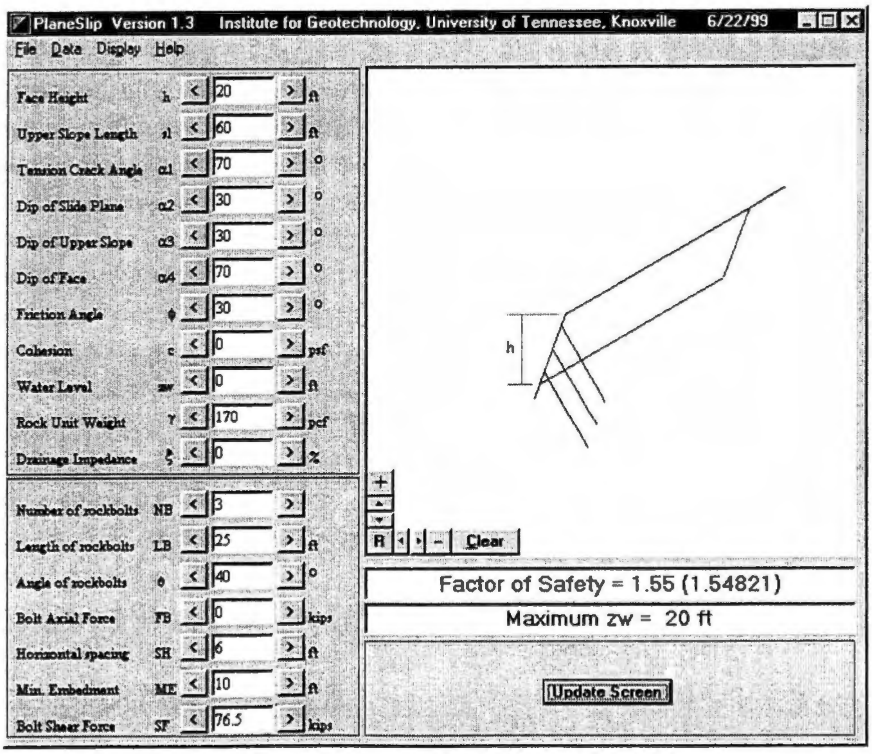

Figure PS - 4b

Example PS - 5 Drainage Impedance

Source: Joshua Cole

Orientation Data:

Discontinuity Type

Slope Face Dip	75°
Top Face Dip	30°
Sliding Plane Dip	30°
Tension Crack Dip	80°
Slope Geometry:	
Face Height	10 m
Upper Slope Length	15 m
Mechanical Parameters:	
Friction Angle	45°
Cohesion	0 kPa
Water Level	4 m
Unit Weight	25 kN/m^3
Drainage Impedance	-50 %
Output:	
Factor of Safety	1.52
Max. Water Level	9.41 m

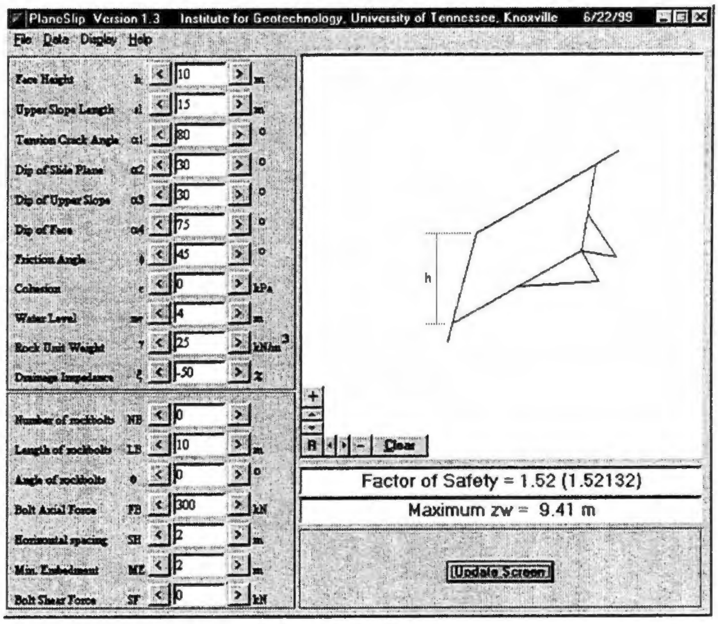

Figure PS - 5a

Discussion:

To access Example 5 go to **Data ⇒ Examples ⇒ Example 5 (Free Draining Slope)**. Turn off the variables diagram and adjust the size and position of the cross-section as desired. Now your screen should be similar to the one pictured in Figure PS - 5a.

This example will focus on the parameter entitled "Drainage Impedance". This parameter allows the user to model drainage conditions at the toe of the slope more accurately. If drainage at the toe of the slope is obstructed, then a positive value of drainage impedance is used to model the situation. For cases where drainage at the toe of the slope is expedited, the drainage impedance value will be negative. The negative value of drainage impedance simply moves the point at which the water pressure distribution on the slide plane reaches atmospheric pressure. For example, the slide plane may be highly eroded near the slope face and even back into the slope (Figure PS-5b). In this case the water flowing along the slide plane does not meet atmospheric pressure at the toe but farther back along the slide plane. In fact, the free flow of water is the most likely cause of weathering and erosion along the slide plane.

Values of drainage impedance range from -90 % to 100 %. A value of 100 % would indicate that drainage is completely impeded for the slope. This will result in an increased water pressure distribution on the slide plane and a lower factor of safety. On

the other hand, -90 % signifies that water reaches atmospheric pressure at a point 90 % of the slide plane length back into the slope. Thus the water pressure distribution would be drastically reduced and the factor of safety increased. Example 5 begins with a value of
-50 % for the drainage impedance. This means that the water pressure distribution goes to zero (i.e. reaches atmospheric pressure) at a point halfway along the slide plane. The initial factor of safety is 1.52. If the drainage impedance is lowered even more to -90%, the factor of safety should rise to 1.61. Raising the drainage impedance back to the neutral value of 0 % gives a factor of safety of 1.41.

Figure PS - 5c shows three different water pressure distributions. The first distribution is for drainage impedance equal to +50%. The second for drainage impedance equal to 0%. And the final distribution is for a drainage impedance of -50%. This figure illustrates how *PlaneSlip* handles water pressure based on the drainage conditions of the slope.

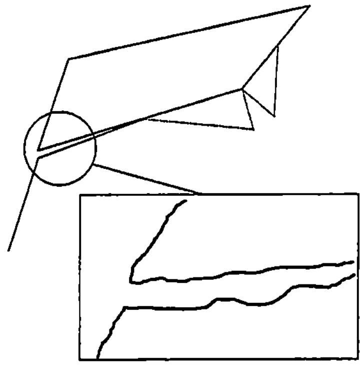

Figure PS - 5b. Assumed water pressure distribution for open fracture.

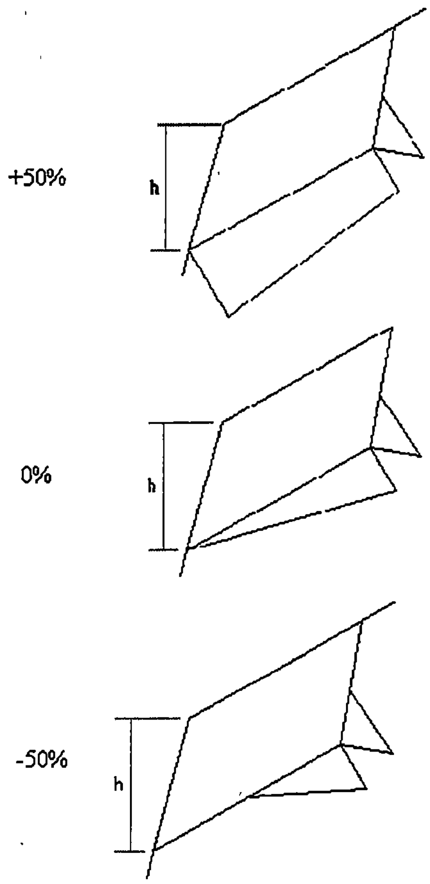

Figure PS - 5c. Variation of water pressure distribution with respect to drainage impedance.

CHAPTER 3. *WedgeSlip* EXAMPLES

3.1 Limiting Equilibrium

The term "limiting equilibrium" means that the forces tending to induce sliding exactly balance the forces resisting sliding. The *Factor of Safety* is defined as the ratio of the total resisting force to the total driving force. For wedge sliding including water pressure and rock bolts, the factor of safety equation is as follows. See Table A.2 for definition of variables.

$$FS = \frac{[N_i^{'} + N_i^{'} + N_b F_b \mathrm{Cos}\beta]\mathrm{Tan}\phi + N_b S_b + (c_1 A_1 + c_2 A_2)}{W \mathrm{Sin}\psi_i - N_b F_b \mathrm{Sin}\beta} \quad (3)$$

Table A.2. Definition of Variables (*WedgeSlip*)

Variable	Description
N'_1, N'_2	Effective normal forces on planes 1 and 2; $N_i' = N_i - u_i A_i$
ϕ_1, ϕ_2	Friction angle of planes 1 and 2
c_1, c_2	Cohesive strengths of planes 1 and 2
A_1, A_2	Area of planes 1 and 2
W	Weight of the wedge
ψ_i	Plunge of the line of intersection of planes 1 and 2
u_1, u_2	Average water pressure on planes 1 and 2
N_b	Number of rockbolts
F_b	Tensile force in rockbolts
β	Angle rockbolts make with normal to the failure plane
S_b	Shear strength of rockbolts

3.2 Worked Examples

Example WS - 1 Introduction to Features and Display Options

Source: Limestone Quarry in Alabama (unpublished)

Orientation Data:

Plane	Dip	Dip Direction
1	30	244 (joint)
2	71	343 (joint)
3	0	227 (top face)
4	54	227 (slope face)

Slope Geometry:

Face Height	10 m

Mechanical Parameters:

Friction Angle	30°
Cohesion	0 kPa
Water Pressure	0 kPa
Unit Weight	27 kN/m^3

Output:

Factor of Safety	1
Sliding Mode	Single Plane on Plane 1

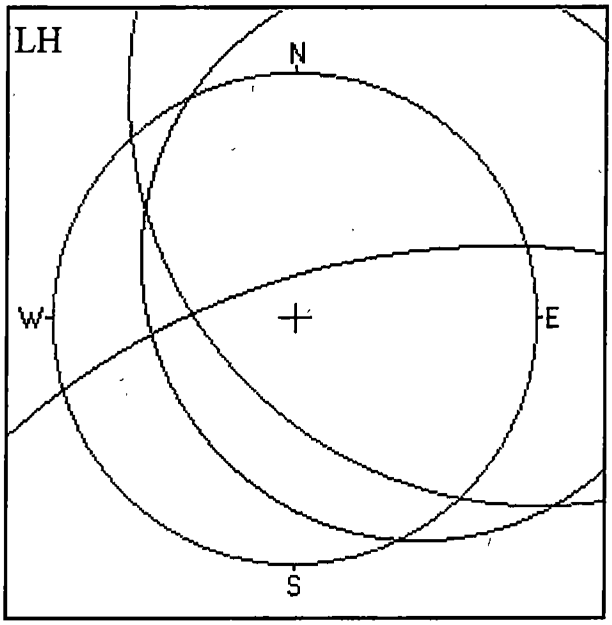

Figure WS - 1a

Discussion:

This example introduces the user to some of the major plotting and calculation options available in *WedgeSlip*. To access Example 1 go to **Data ⇒ Examples ⇒ Example 1 (Limestone Quarry)**.

The first objective of this example is to familiarize the user with the orientation data. First, plot the dip and normal vectors for each plane. To do this go to **Lower Window ⇒ Stereograph(LH).** A submenu should pop up with several plotting options. Simply click on **Plot Dip Vectors** and the dip vectors should appear on the stereographic projection. Use the same process to plot the normal vectors. Each dip and normal vector is labeled (e.g.

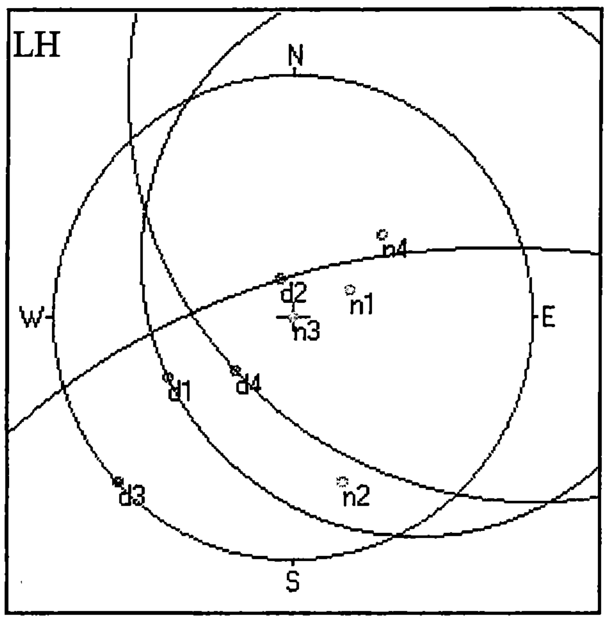

Figure WS - 1b

"d1" is the dip vector for plane 1) according to the plane it is associated with. Note the picture controls in the lower left hand corner of each of the picture boxes. Try adjusting the position and size of both the cross-section and stereographic projection.

The next objective is to illustrate the **auto-redraw function** and the **sliding mode** feature. Start lowering the value for **dip direction 2** to 322 (from 343). Note how the stereographic projection and the slope cross-section change in real-time as the value is lowered. Once you get to 322 the **sliding mode** should change from single plane sliding on plane 1 to double plane sliding.

Another important feature is the **Highlight Removable Wedge** option. To activate this option go to **Lower Window ⇒ Stereograph(LH)**. Click on **Highlight Removable Wedge** and the appropriate area on the stereograph should be shaded in yellow. Now lower **dip direction 1** to 226 (from 244). The removable wedge should change. Removability of wedges is discussed in detail by Goodman and Shi (1985).

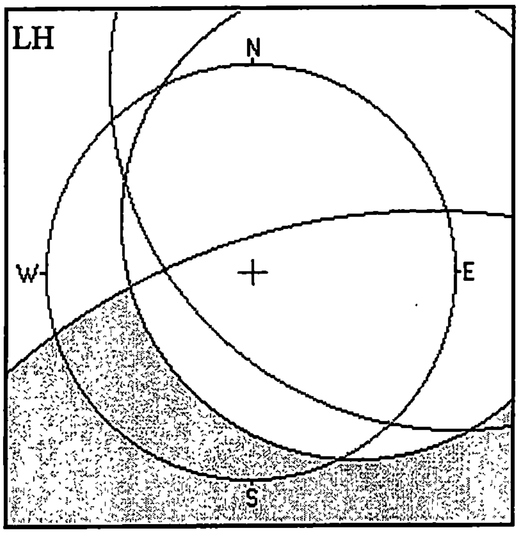

Figure WS - 1c

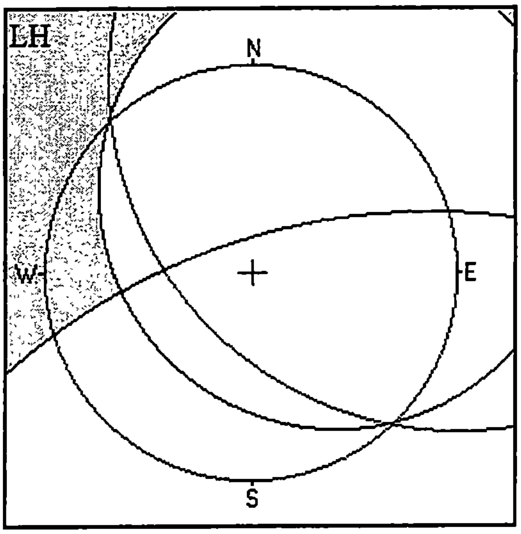

Figure WS - 1d

Now examine the effects of **water pressure.** Click on the button labeled "No Water Pressure". It should change to "Include Water Pressure" and several input features directly below the button should be enabled. The program initially defaults to a calculated value of water pressure on each plane. Begin by zeroing out each water pressure. Now examine how the factor of safety changes when **u1** and **u2** are adjusted. You should notice that the factor of safety is more sensitive to changes in **u1**. Now raise **u1** to 50 kPa. This changes the sliding mode to single plane on plane 2. Another important aspect of the program can now be demonstrated. When *WedgeSlip* determines that the sliding mode is single plane, it detects which parameters affect the stability analysis and which ones don't. In this instance, ϕ_1 has no effect while ϕ_2 has a great effect on the factor of safety.

Example WS - 2 Water Pressure; Sensitivity Analysis

Source: I-40 Wedge (Russell Glass, NCDOT)

Orientation Data:

Plane	Dip	Dip Direction
1	36	250 (joint)
2	61	161 (joint)
3	0	212 (top face)
4	76	212 (slope face)

Slope Geometry:

Face Height	200 ft

Mechanical Parameters:

Friction Angle	30°
Cohesion	0 psf
Water Pressure	0 psf
Unit Weight	160 pcf

Output:

Factor of Safety	0.95
Sliding Mode	Double Plane

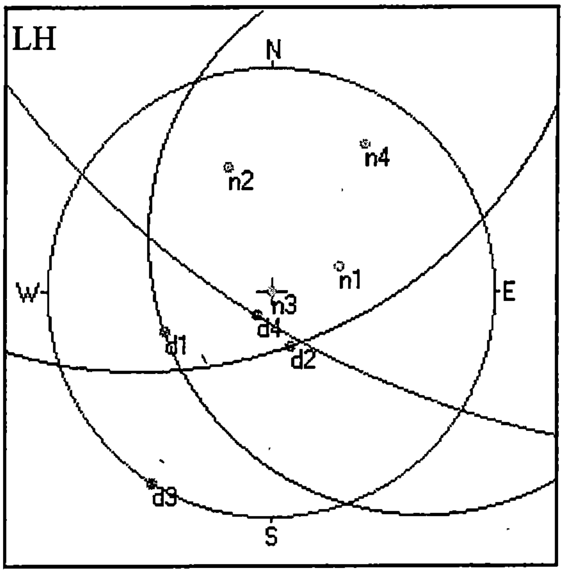

Figure WS - 2a

Discussion:

This example is based on an actual wedge slide that occurred along Interstate 40 just inside the North Carolina border on July 1, 1997. All lanes of Interstate 40 were closed due to continued sliding on the slope. Close to 200,000 cubic yards of material, identified as the Pigeon Siltstone, had to be excavated. Rockbolts, horizontal drains and a Brugg Cable Net system were installed as remediation measures. The information for this example was furnished by F. Russell Glass of the North Carolina Department of Transportation.

To access the data for Example WS - 2 go to **Data ⇒ Examples ⇒ Example 2 (I-40 Wedge).** Plane 1 is identified as a bedding plane. Plane 2 is a through-going joint set. Planes 3 and 4 are the top and slope faces, respectively. The orientation data with the dip and normal vectors for each plane are plotted in Figure WS - 2a. The initial factor of safety is less than one (0.95), indicating that the slope is unstable based on slope geometry alone.

Water pressure was identified as the most likely contributor to slope instability in this wedge slide. Heavy rains in the days that preceded the failure caused water pressures to build up in the slope. Let's perform a small sensitivity analysis to demonstrate how much the factor of safety is affected by changes in water pressure for this geometry. Click on the "No Water Pressure" button. It will change to "Include Water Pressure" and default values of water pressure (based on slope geometry) will be entered in the stability calculations. The default value is 2080 psf for this slope geometry. With this water pressure acting on the wedge, the factor of safety drops to 0.60 (Figure WS - 2b). Now zero out the water pressure on plane 2 and begin to adjust the water pressure on plane 1. Examine the factor of safety at regular increments of water pressure (for example, 1000 psf). The following table presents the results of a sample sensitivity analysis for this slope.

u_1 (psf)	u_2 (psf)	FS
1000	0	0.84
2000	0	0 (Single Plane Sliding on Plane 2)
3000	0	0 (Single Plane Sliding on Plane 2)
0	1000	0.89
0	2000	0.83
0	3000	0.77

Table WS - 1. Sample sensitivity analysis in *WedgeSlip.*

As illustrated by the above table, the slope is much more sensitive to changes in the water pressure on plane 1. At 2000 psf, the effective normal force on plane 1 is negated and the sliding occurs along plane 2 only. The results of this example show that the slope in this case is highly susceptible to changes in water pressure, especially along plane 1. Thus, *WedgeSlip* verifies that heavy rains and a build up of water pressure in the slope were indeed the culprit of the I-40 wedge slide.

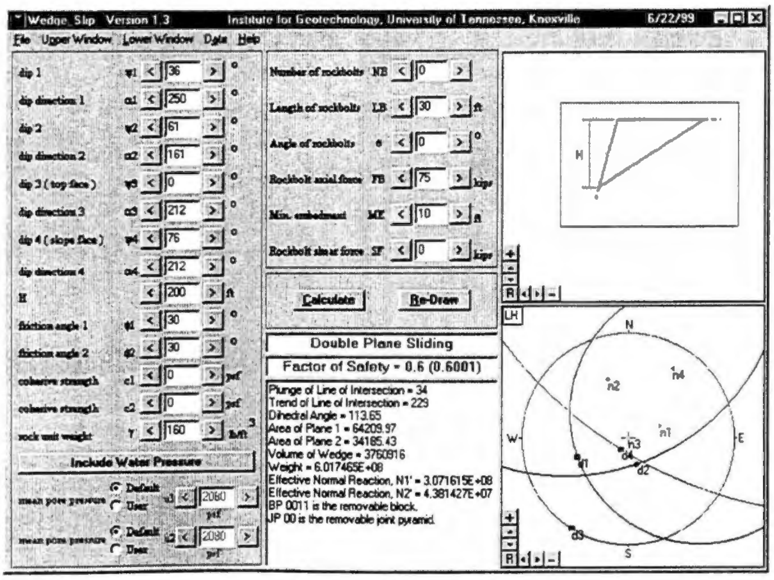

Figure WS - 2b

Example WS - 3 Symmetric Wedge

Source: Dr. Matthew Mauldon

Orientation Data:

Plane	Dip	Dip Direction
1	54.74	315 (joint)
2	54.74	45 (joint)
3	0	180 (top face)
4	90	0 (slope face)

Slope Geometry:

Face Height 1 m

Mechanical Parameters:

Friction Angle 30°
Cohesion 0 kPa
Water Pressure 0 kPa
Unit Weight 25 kN/m^3

Output:

Factor of Safety 0.71
Sliding Mode Double Plane

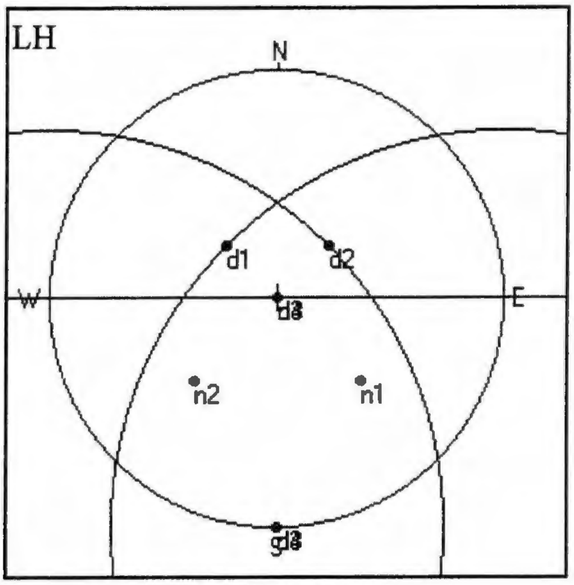

Figure WS - 3a

Discussion:

The following example is a case designed to utilize symmetry for ease of calculation. The wedge that is to be analyzed can be visualized as a portion of a cube. For this example, the sides of the cube are set at an arbitrary length of 2.

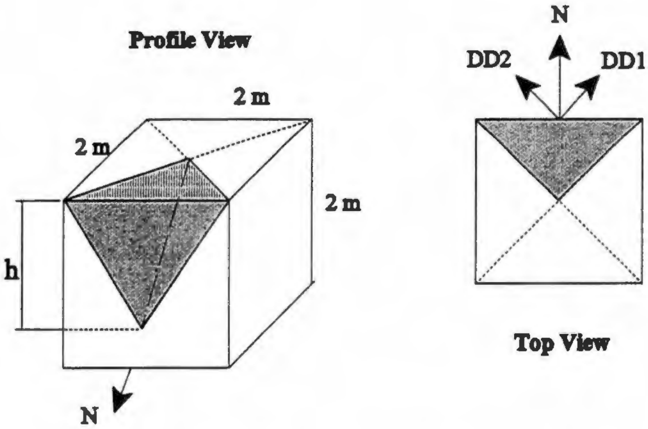

Figure WS - 3b. Wedge slide schematic.

To access the data for Example WS - 3 go to **Data ⇒ Examples ⇒ Example 3 (Symmetric Wedge).** The orientation data for this example is shown in Figure WS - 3a. Since the wedge is symmetric, the limiting equilibrium analysis is simplified. The table below (Table WS - 2) presents the results of a verification exercise done using this symmetric data. Try changing various quantities in *WedgeSlip* and verify that the results match those given in the table.

Table WS - 2. *WedgeSlip* Verification Exercise

4/10/99

h	Vol	γ	Wt.	ψ	α	Area	φ	c	N	T	S	β	u	N'	Fr	Fd	FS	FS (*WS*)
1	0.33	26	8.67	45.00	109.47	0.87	30	0	0	1	1	10	0	3.75	4.33	6.13	0.71	0.71
1	0.33	27	9.00	45.00	109.47	0.87	30	0	0	1	1	10	0	3.90	4.50	6.36	0.71	0.71
1	0.33	28	9.33	45.00	109.47	0.87	30	0	0	1	1	10	0	4.04	4.67	6.60	0.71	0.71
1	0.33	29	9.67	45.00	109.47	0.87	30	0	0	1	1	10	0	4.19	4.83	6.84	0.71	0.71
1	0.33	25	8.33	45.00	109.47	0.87	10	0	0	1	1	10	0	3.61	1.27	5.89	0.22	0.22
1	0.33	25	8.33	45.00	109.47	0.87	20	0	0	1	1	10	0	3.61	2.63	5.89	0.45	0.45
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	0	3.61	4.17	5.89	0.71	0.71
1	0.33	25	8.33	45.00	109.47	0.87	40	0	0	1	1	10	0	3.61	6.06	5.89	1.03	1.03
1	0.33	25	8.33	45.00	109.47	0.87	30	5	0	1	1	10	0	3.61	12.83	5.89	2.18	2.18
1	0.33	25	8.33	45.00	109.47	0.87	30	10	0	1	1	10	0	3.61	21.49	5.89	3.65	3.65
1	0.33	25	8.33	45.00	109.47	0.87	30	15	0	1	1	10	0	3.61	30.15	5.89	5.12	5.12
1	0.33	25	8.33	45.00	109.47	0.87	30	20	0	1	1	10	0	3.61	38.81	5.89	6.59	6.59
1	0.33	25	8.33	45.00	109.47	0.87	30	0	2	1	1	10	0	4.81	7.56	5.55	1.36	1.36
1	0.33	25	8.33	45.00	109.47	0.87	30	0	4	1	1	10	0	6.02	10.95	5.20	2.11	2.11
1	0.33	25	8.33	45.00	109.47	0.87	30	0	6	1	1	10	0	7.23	14.34	4.85	2.96	2.96
1	0.33	25	8.33	45.00	109.47	0.87	30	0	8	1	1	10	0	8.43	17.74	4.50	3.94	3.94
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	5	1	10	0	6.62	8.65	5.02	1.72	1.72
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	10	1	10	0	9.64	12.13	4.16	2.92	2.92
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	15	1	10	0	12.65	15.61	3.29	4.75	4.75
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	20	1	10	0	15.67	19.09	2.42	7.89	7.89
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	5	10	0	4.21	9.86	5.72	1.72	1.72
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	10	10	0	4.21	14.86	5.72	2.60	2.60
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	15	10	0	4.21	19.86	5.72	3.47	3.47
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	20	10	0	4.21	24.86	5.72	4.35	4.35
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	20	0	4.18	5.83	5.55	1.05	1.05
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	40	0	4.08	5.71	5.25	1.09	1.09
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	60	0	3.91	5.52	5.03	1.10	1.10
1	0.33	25	8.33	45.00	109.47	0.87	30	0	1	1	1	80	0	3.71	5.29	4.91	1.08	1.08
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	1	2.74	3.17	5.89	0.54	0.54
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	2	1.88	2.17	5.89	0.37	0.37
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	3	1.01	1.17	5.89	0.20	0.20
1	0.33	25	8.33	45.00	109.47	0.87	30	0	0	1	1	10	4	0.14	0.17	5.89	0.03	0.03
h	Vol	γ	Wt.	ψ	α	Area	φ	c	N	T	S	β	u	N'	Fr	Fd	FS	FS (*WS*)

Example WS - 4 Comparison of *WedgeSlip* to Other Analysis Methods

Source: B.K. Low

Orientation Data:

Plane	Dip	Dip Direction
1	45	105 (joint)
2	70	235 (joint)
3	12	185 (top face)
4	65	185 (slope face)

Slope Geometry:

Face Height	30.55 m

Mechanical Parameters:

Friction Angle 1, ϕ_1	30°
Friction Angle 2, ϕ_2	20°
Cohesion 1, c_1	24 kPa
Cohesion 2, c_2	48 kPa
Water Pressure	66.7 kPa
Unit Weight	25 kN/m^3

Output:

Factor of Safety	1.32
Sliding Mode	Double Plane

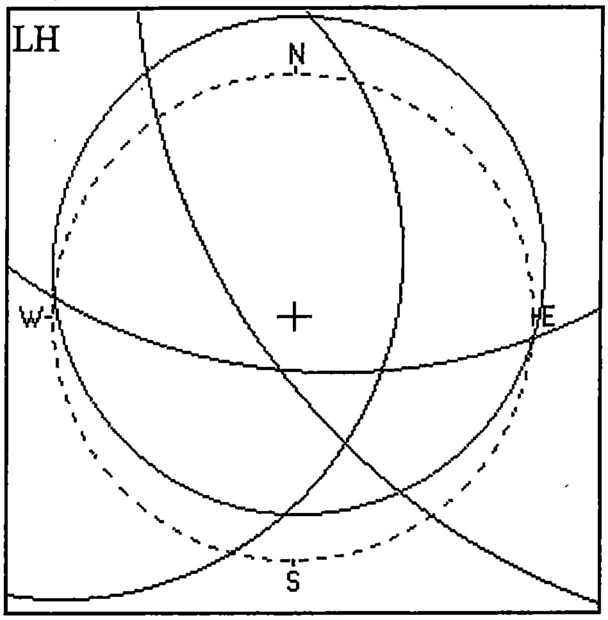

Figure WS - 4a

Discussion:

This example is taken from a paper by B.K. Low entitled "Reliability Analysis of Rock Wedges". To access the data for this example go to **Data ⇒ Examples ⇒ Example 4 (B.K. Low, 1997)**. The orientation data for this example is shown in Figure WS - 4a. Low uses this example to verify his closed-form equations by comparing them with the Hoek and Bray vectorial method (Hoek and Bray, 1981). The factor of safety calculated in *WedgeSlip* is 1.324. This result agrees with both Low's and Hoek and Bray's methods.

Now let's examine how *WedgeSlip* compares with both methods as far as sliding mode and factor of safety is concerned. The subsequent data is used for all cases: h = 20 meters; $\gamma = 25$ kN/m^3; $\gamma_w = 10$ kN/m^3; $\phi_1 = 30°$; $\phi_2 = 35°$; $c_1 = 25$ kPa; $c_2 = 0$ kPa; Slope face = 65/045 (Dip/Dip Direction); Top face = 10/045. Note that $\gamma_w = 10$ kN/m^3 is used in both Low's and Hoek and Bray's method. *WedgeSlip* uses a value of 9.81 kN/m^3. This may create a slight discrepancy between the methods, especially the ones where water pressure plays a greater role.

Table WS - 3. Comparison of *WedgeSlip* to other stability analysis methods.

Low's Equation	β_1	δ_1	β_2	δ_2	G_w	Mode	FS
H & B Vectorial	Dip Direction 1	Dip 1	Dip Direction 2	Dip 2	u	Mode	FS
WedgeSlip	Dip Direction 1	Dip 1	Dip Direction 2	Dip 2	u	Mode	FS
CASE 1	7	47	27	70	0.45	Plane 1	0.627
H & B	52	47	18	70	30.0	Plane 1	0.627
WedgeSlip	52	47	18	70	30.0	Plane 1	0.627
CASE 2	111	23	32	100	0.80	Plane 1	2.164
H & B	294	23	257	80	53.333	Plane 1	2.164
WedgeSlip	294	23	257	80	53.333	Plane 1	2.164
CASE 3	103	33	29	72	0.50	BiPlane	1.594
H & B	302	33	74	72	33.333	BiPlane	1.594
WedgeSlip	302	33	74	72	33.333	BiPlane	1.594
CASE 4	76	37	41	50	0.88	BiPlane	0.929
H & B	329	37	86	50	58.667	BiPlane	0.929
WedgeSlip	329	37	86	50	58.667	BiPlane	0.929
CASE 5	85	110	18	20	0.72	Plane 2	1.172
H & B	140	70	63	20	48.000	Plane 2	1.172
WedgeSlip	140	70	63	20	48.000	Plane 2	1.172
CASE 6	59	101	40	28	0.52	Plane 2	0.793
H & B	166	79	85	28	34.667	Plane 2	0.793
WedgeSlip	166	79	85	28	34.667	Plane 2	0.793
CASE 7	51	58	56	76	0.70	Floats	0
H & B	354	58	101	76	46.667	Floats	0
WedgeSlip	354	58	101	76	46.667	Floats	0
CASE 8	30	88	57	78	0.74	No Wedge	
H & B	15	88	102	78	49.333	No Wedge	
WedgeSlip	15	88	102	78	49.333	No Wedge	

Example WS - 5 Parameter Studies

Source: TRB Special Report 247

Orientation Data:

Plane	Dip	Dip Direction
1	45	265 (joint)
2	48	168 (joint)
3	10	196 (top face)
4	76	196 (slope face)

Slope Geometry:

Face Height	30 m

Mechanical Parameters:

Friction Angle 1, ϕ_1	35°
Friction Angle 2, ϕ_2	25°
Cohesion 1, c_1	20 kPa
Cohesion 2, c_2	10 kPa
Water Pressure	0 kPa
Unit Weight	25 kN/m^3

Output:

Factor of Safety	1.18
Sliding Mode	Double Plane

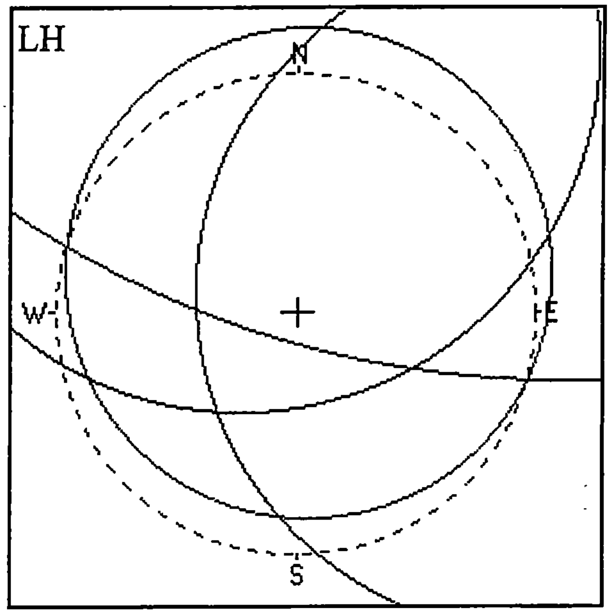

Figure WS - 5a

Discussion:

The following example is taken from the TRB Special Report 247 "Landslides: Investigation and Mitigation". To access the data for this example go to **Data ⇒ Examples ⇒ Example 5 (TRB Special Report 247, 1996)**. The orientation data for this example is shown in Figure WS - 5a.

The initial factor of safety in *WedgeSlip* is 1.18. This value is slightly different from the 1.23 calculated in the TRB report. The TRB report truncates intermediate geometry and force values at the second decimal place, whereas *WedgeSlip* carries much more precision in the values throughout the stability calculations. Nevertheless, both of these values are not acceptable for most slope engineering design. Therefore, rock reinforcement and other stabilization methods should be considered for this particular geometry.

Another factor in the stability calculations are the parameters obtained through laboratory testing. The TRB report suggests that if poor blasting practice had been utilized in the excavation process, it is possible that the cohesion along the discontinuities could have been destroyed. We can examine this scenario in *WedgeSlip*. Adjust the two cohesive strength values to 0 kPa to model this situation. The factor of safety should drop to 1.01 (Figure WS - 5b), which agrees with the TRB report. This illustrates the importance of controlled blasting practice when creating permanent rock slopes.

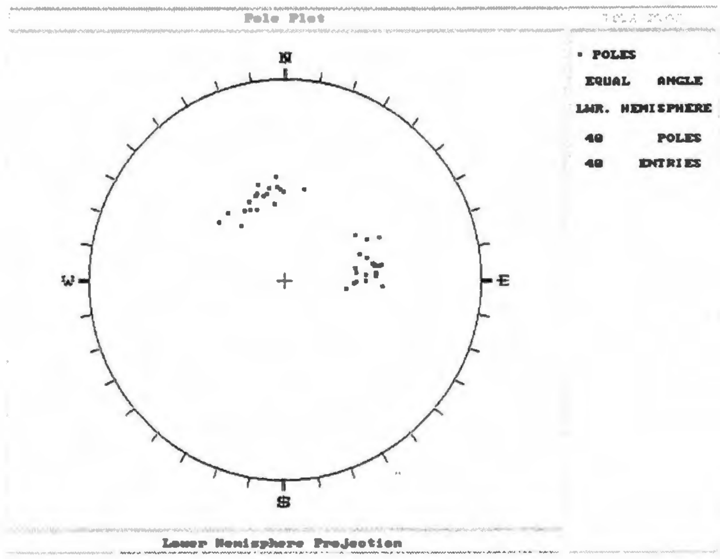

Figure WS - 5b

Another uncertainty is in the orientations of the discontinuities which make up the wedge. The orientations are usually determined from analysis of preferably large, unbiased data sets gathered in the field. This orientation data is then typically plotted as poles on a stereographic projection (Figure WS - 5b) and analyzed to determine a preferred or "best-fit" orientation for each major discontinuity. Contouring is a common statistical method used to determine preferred orientation. Figure WS - 5c shows an example of a contour plot.

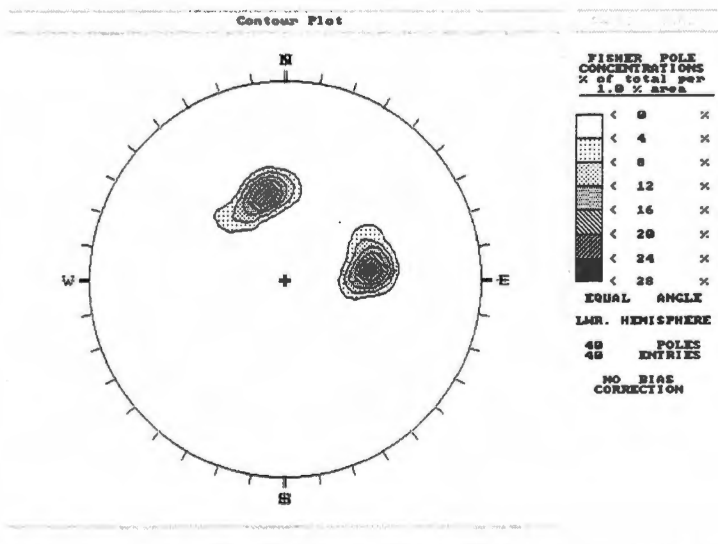

Figure WS - 5c

CHAPTER 4. *RockSlip* EXAMPLE

4.1 Potential Energy Minimization

RockSlip deals with failures involving multiple or curved sliding surfaces. The analysis procedure, which was originally developed for stability analysis in folded rocks, is based on minimization of potential energy. For a detailed explanation of the potential energy minimization method please refer to Mauldon and Ureta (1996) and Mauldon et. al. (1998). Due to the lengthy mathematical formulations involved, an explanation of the method will not be presented here.

4.2 Additional Assumptions

The following additional assumptions are made in the potential energy model:

- Each contact face of the rock block is assumed to have a normal stiffness of k_n, whereas the previously published work employed a uniform spring stiffness constant for all contact surfaces.
- An elastic, conservative system is assumed to determine the distribution of normal forces that minimizes the potential energy of the system.
- A local coordinate system is defined with the Z axis parallel to the fold axis and X and Y in the plane orthogonal to the fold axis.
- Each plane has a length L_i in the XY plane, and since this is a prismatic block, the other dimension of the contact plane will be taken as a unit length in the Z (fold axis) direction.

4.3 Worked Example

Example RS - 1 *RockSlip* Introduction

Source: Biltmore, TN

Orientation Data:	
Fold Axis Trend	228°
Fold Axis Plunge	11°
Outcrop Dip	75°
Outcrop Dip Dir.	225°
Slope Geometry:	
Upper Slope Length	10 ft
Mechanical Parameters:	
Friction Angle	20°
Water Level	0 ft
Drainage Impedance	0 %
Cohesion	0 psf
Unit Weight	160 pcf

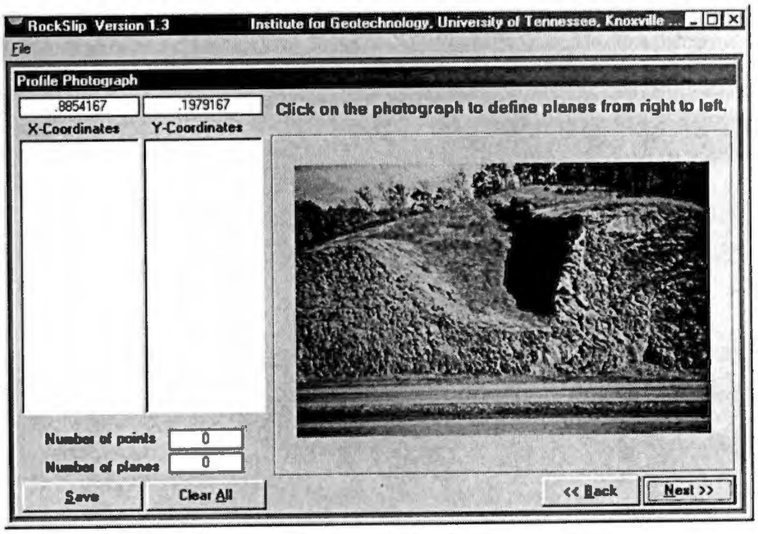

Figure RS - 1a

Discussion:

This example is taken from field data obtained from a site in Biltmore, Tennessee as part of Scott Arwood's thesis work. The slope stability problems encountered on this site were the initial impetus behind the development of the *ROCKSLIP* package of programs.

The bitmap that is used in this example is entitled "Bilt1a.bmp". Click on **File ⇒ Open Bitmap** and go to the directory "C:\Program Files\Rs\Images" to find "Bilt1a.bmp". Your screen should now look like Figure RS - 1a.

The next step is to define the failure planes. This is accomplished by pointing and clicking the mouse to define each plane. Note that the planes must be defined from right to left. *RockSlip* will yield a message saying that the factor of safety is infinitely high if the planes are not defined correctly. Try plotting only two failure planes (traditional wedge configuration) at first. Click on the "Next" button to move through the forms. The outcrop data form should already have the example data entered by default. To calculate the factor of safety (FS), click on "Next" on the outcrop data form and the results form should appear. The factor of safety should be between 2.3 and 2.7 for the default data. Note that the orientation of the two failure planes affects the calculated FS. Now try using three planes to describe the failure surface. Click "Back" until the profile photograph form is reached. Click "Clear All" and the previously defined failure surfaces should disappear. Depending on how the three planes are selected the factor of safety should be between 1.2 and 1.6 for the default data.

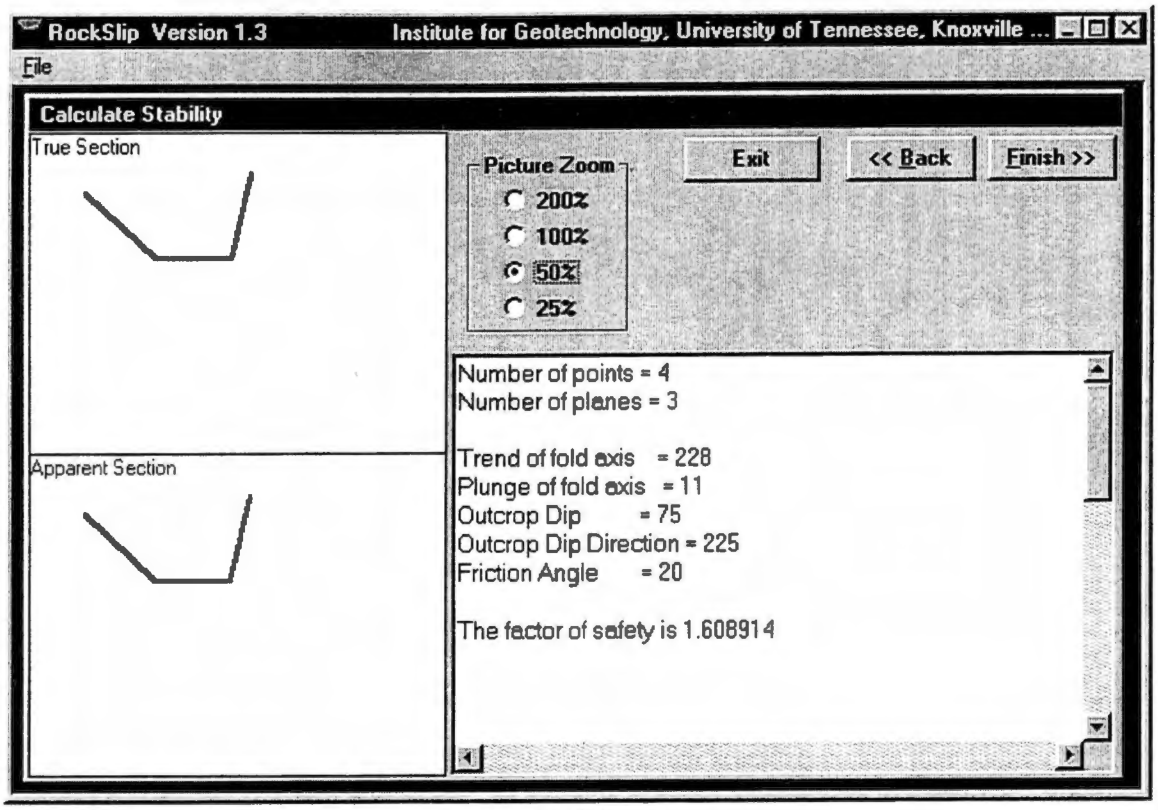

Figure RS - 1b

Another important output on the results form is the apparent and true section diagrams found on the left side of the form. These diagrams illustrate the difference between the apparent section which is defined on the bitmap of the outcrop and the true section which is being analyzed. This relationship is based on the trend of the fold axis and the dip direction of the outcrop. Try lowering and raising either one of these values while holding the other constant. You should notice a more pronounced difference between the true and apparent sections. Also, the factor of safety should be affected. Do these changes make sense with the data? Figure RS - 1b shows the results form after lowering the dip direction of the outcrop. Notice the difference between the true and apparent section.

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APPENDIX B:
TDOT REGION ONE GEOTECHNICAL REMEDIATION PROJECTS: 1973 - 1995

The purpose of the following group of charts is to present 22 years worth of TDOT report data in a concise and easy to understand format. The data compiled represents active TDOT projects and their start dates (if available). Since some projects spanned several years they show up several times in the yearly counts. Therefore, these graphs should not be misinterpreted as a measure of new projects started each year, but rather a quantification of the magnitude of remedial work TDOT had to perform each year. Landslide projects are focused on in this brief report because they exhibit a striking relationship to the rate of occurences through the years. Also certain counties seem to be more prone to failures, as exhibited by the last set of charts. The types of geotechnical projects are listed according to the determination made in the original TDOT Region One Project Status Reports.

Note: L = Landslide, C = Cut slope, F = Fill Slope, S = Subsidence, SH = Sinkhole, and B = Backfill.

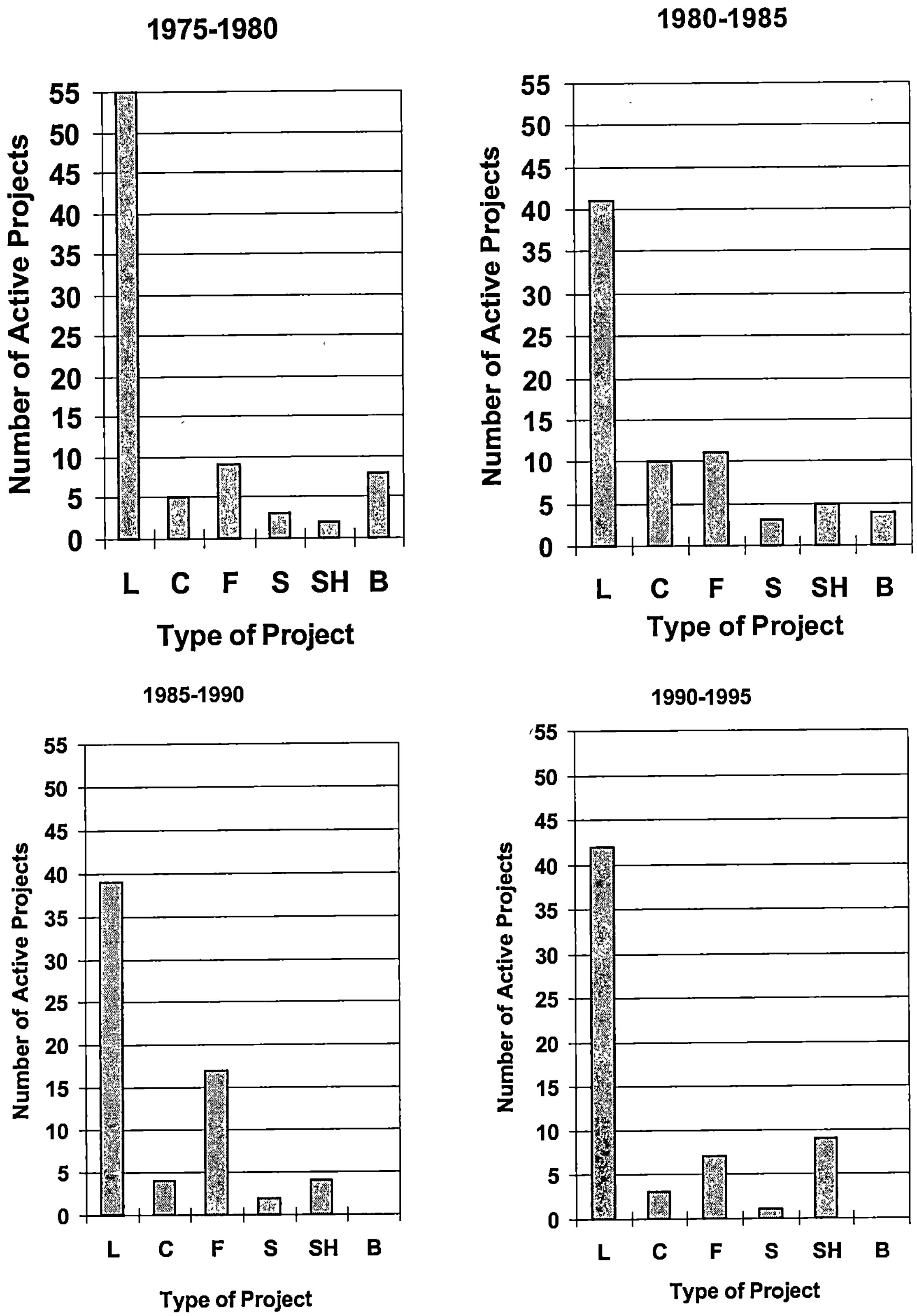
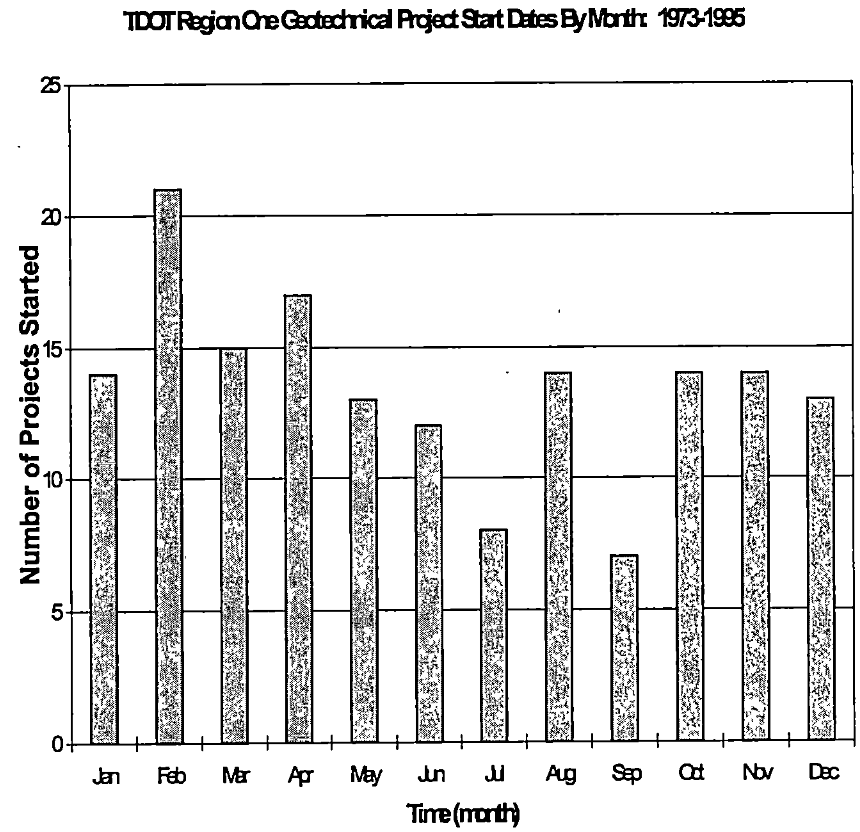
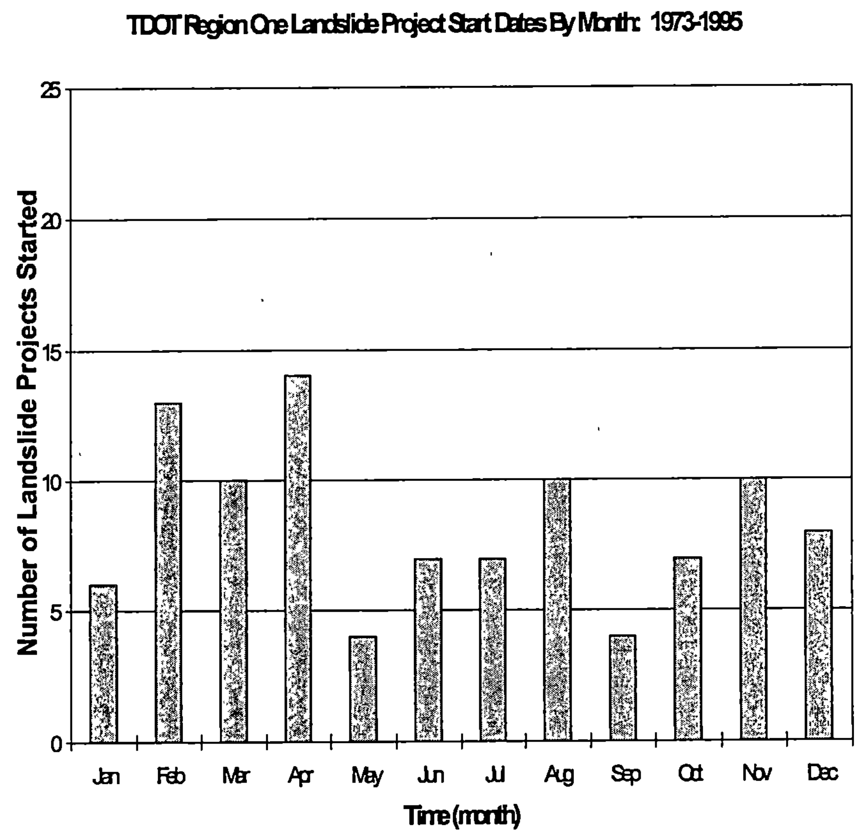


Figure B.1 TDOT Region One active projects by five-year time period (1975 - 1995)

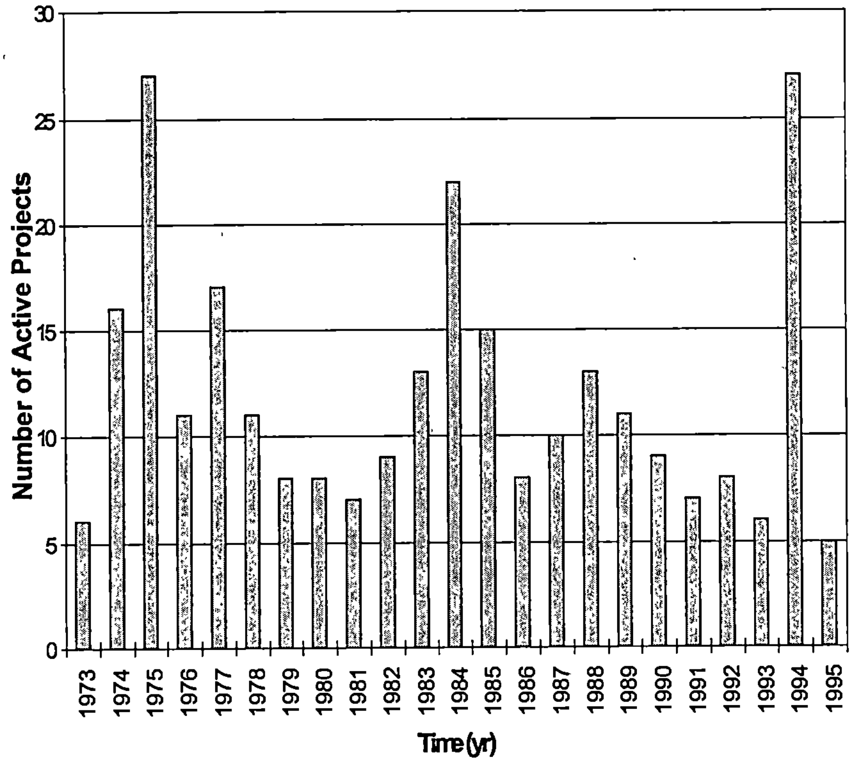
Note: L = Landslide, C = Cut slope, F = Fill Slope, S = Subsidence, SH = Sinkhole, and B = Backfill.



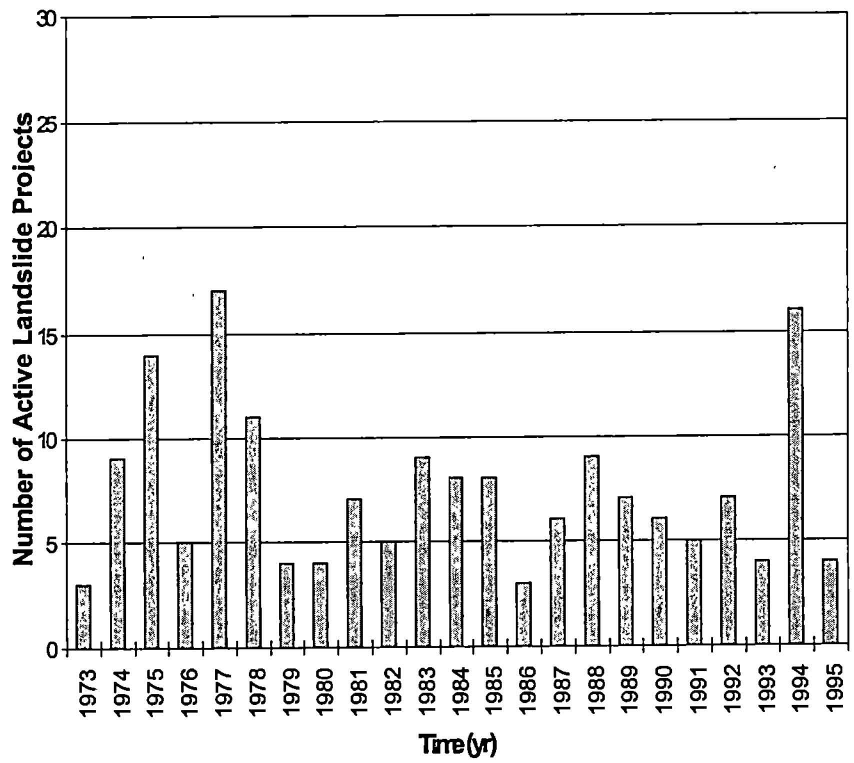


Note: L = Landslide, C = Cut slope, F = Fill Slope, S = Subsidence, SH = Sinkhole, and B = Backfill.

TDOT Region One Active Geotechnical Projects By Year: 1973-1995

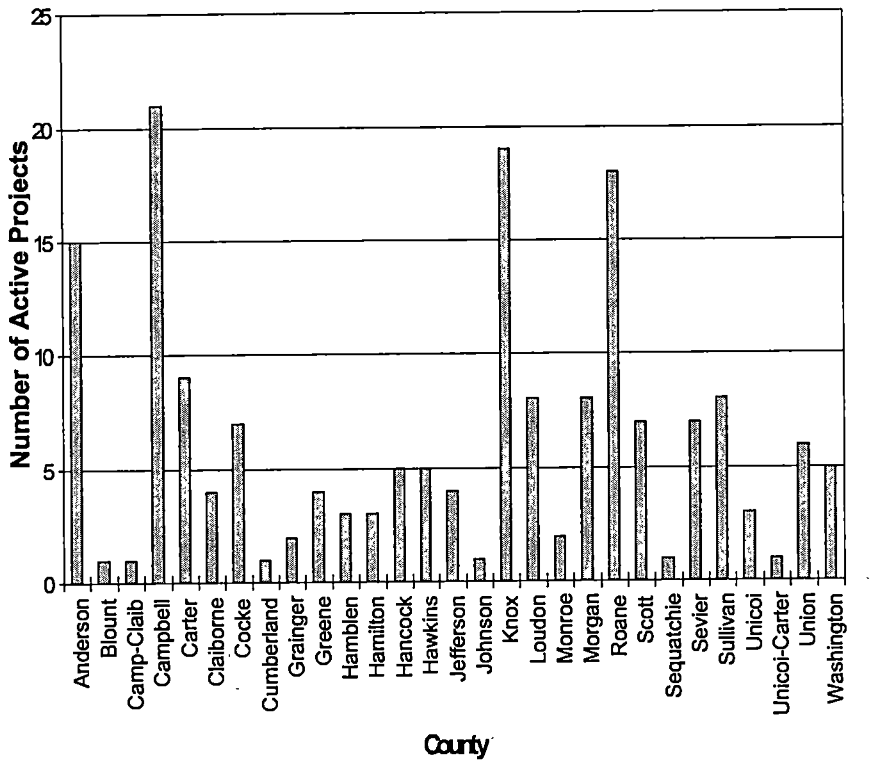


TDOT Region One Active Landslide Projects By Year: 1973-1995

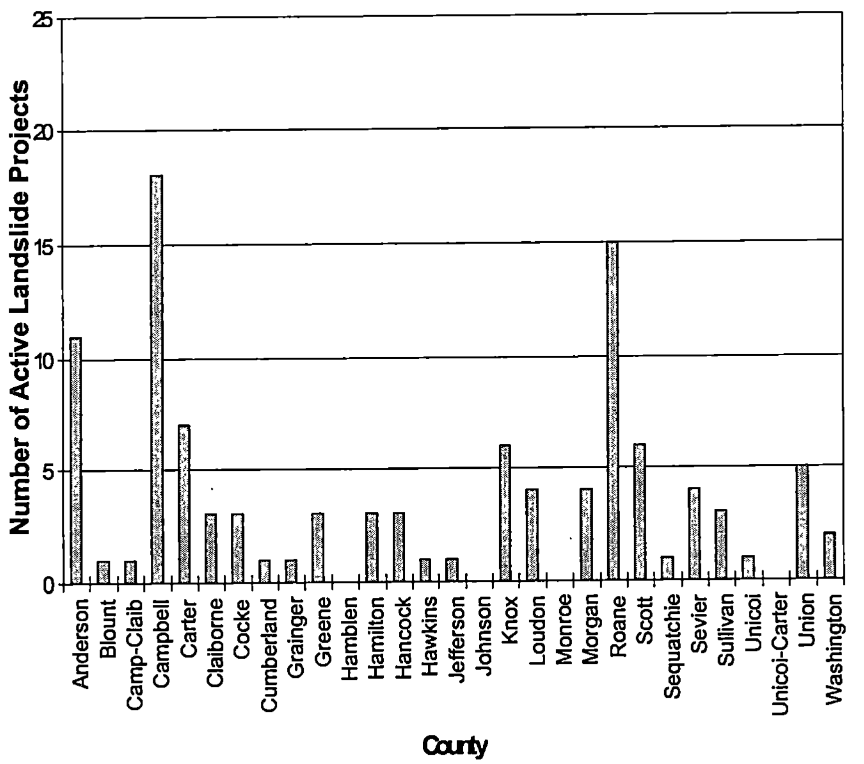


Note: L = Landslide, C = Cut slope, F = Fill Slope, S = Subsidence, SH = Sinkhole, and B = Backfill.

TDOT Region One Active Geotechnical Projects By County: 1973-1995



TDOT Region One Active Landslide Projects By County: 1973-1995



Note: L = Landslide, C = Cut slope, F = Fill Slope, S = Subsidence, SH = Sinkhole, and B = Backfill.

VITA

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