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USER'S MANUAL

ROCKPACK III for Windows

ROCK Slope Stability Computerized Analysis PACKage

PART ONE - STEREONET ANALYSES

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RockPack III

The complete rock slope stability analysis solution: from field data collection, to kinematic stereonet analyses, to safety factor calculations, to remediation.

Welcome to ROCKPACK III for Windows

These programs have been tested and are believed to be reliable engineering tools. No responsibility is assumed by the authors or the distributors for any errors, mistakes, or misrepresentations that may occur from any use of these programs. If not satisfied, purchaser may return materials within 30 days of receipt for refund.

Be sure to register !!

Be sure to register your software by mailing the enclosed registration form, or emailing your software serial number (located on your CD) along with your address and phone number to **cwatts@radford.edu** or **drgillia@radford.edu.** This will enable you to receive notifications regarding changes and upgrades.

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OVERVIEW AND DISCLAIMERS

A rock mass is only as strong as the weaknesses that it contains. Those weaknesses, called discontinuities, must be carefully mapped and analyzed in order to predict the stability of blocks within the rock mass. The ROCKPACK III programs were designed to help manage the study of rock mass discontinuities and the potential failures that they might cause.

Rock mass discontinuities include such geologic structures as faults, joints, bedding planes, and metamorphic foliations as described in Chapter 3. With such geologic control over stability, rock slope failures tend to occur as one of the types illustrated in Figure P-1. Discontinuity orientations that can lead to these failure types are plotted on the stereonets here as dip vectors, described in Chapter 4. For circular failures, programs such as STABL and XSTABL are recommended (see references).

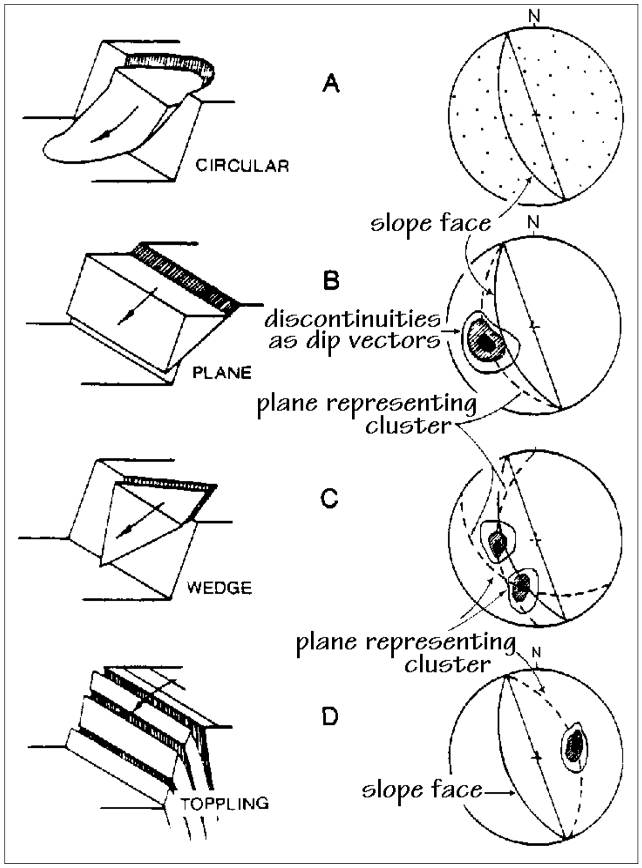

Figure P-1. Types of failures likely to occur in rock slopes based on discontinuities shown as dip vectors, modified from Hoek and Bray, 1981.

Unstable rock masses are often extremely complex assemblages of geologic structures and rock types, both of which affect slope behavior. The user is urged to seek the services of competent engineering and geologic consultants whenever site conditions exceed in-house expertise.

This manual assumes that the user has a basic working knowledge of rock slope stability theory; hence detailed theory will not be discussed here. For a review of the principles of rock slope analysis, the reader is directed to the references cited at the end of this manual.

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1.0 ROCKPACK III - WHAT'S NEW

(For MS Windows)

1.1 INTRODUCTION

RockPack III for Windows is the 2003 release in the RockPack line of software. Originally written for the DOS operating environment 20 years ago, RockPack has had a long and successful history of usage around the world as a simple, practical, no nonsense solution to evaluating the stability of rock slopes. There have been many changes in operating environments over the past 2 decades, but RockPack's flexibility and unique set of tools has allowed it to remain immensely popular throughout its life span.

Listed below are just a few of the features you will find in RockPack III for Windows:

Data Entry:

- Customizable spreadsheet-style entry of field data
- Easy conversion of old RockPack II data files

Stereonet Analyses:

- Simple stereonet analyses for plane, wedge, and toppling failures
- Stereonet plotting in BOTH pole and dip vector formats with "Quick Switch" capability for rapid comparison
- Mouse driven wedge failure analyses in pole or dip vector format
- One button save, puts bit mapped stereonet drawings on your hard drive for later use as both pole and dip vector plots

Safety Factor Calculations:

- New easy-to-use Safety Factor programs with onscreen diagrams, make data entry simple
- "Units" button allows direct entry in either British Imperial (USA) units or SI units (metric), and automatically converts between the two as needed.
- Print results directly to any printer OR save results as report files for later use
- Artificial support calculation, graphing, seismic loading, surcharges, water pressures and more

This is an exciting time for old and new RockPack users alike. New improved graphics capabilities, a standard MS Windows interface, and streamlined installation routine are sure to make RockPack III for Windows a hit. Please register and watch for news regarding future RockPack upgrades. We welcome your comments and suggestions!

2.0 INSTALLATION OF ROCKPACK III FOR WINDOWS

2.1 SYSTEM REQUIREMENTS

RockPack III for Windows, minimum requirements:

MS Windows© Operating System (95, 98, Me, NT 4, 2000, NT 5, XP)
50 mb hard drive space
Pentium processor or higher
SVGA Graphics card
Mouse
CD-ROM drive

2.2 INSTALLATION AND OPERATION

The installation of RockPack III for Windows is very straightforward. Simply insert the CD-ROM into the CD-ROM drive and close. In most cases, the installation software will automatically begin with a dialogue screen. Follow the directions on the screen.

If the dialogue box does not automatically open, then go to “My Computer” > “D (or whatever your CD drive name is on your computer) > Setup.exe. Double click on Setup.exe to begin the installation and bring up the dialogue box.

During setup, you may change the directory location of the software. The default is C:\ROCKPACK. In most instances, changing the default is not necessary. Simply press <Enter> to accept the defaults.

Once software installation is complete, you may run RockPack III from the Windows Start menu. Click “Start > Programs > RockPack III > RockPack.exe. Or, navigate to the executable file through Windows Explorer to:

C:\Program Files\RockPack\RockPack.exe

and double-click it to begin the program. Also, shortcut icon can be placed on your desktop from this location with a right mouse click, drag RockPack.exe to the desktop, and select “Create Shortcut.”

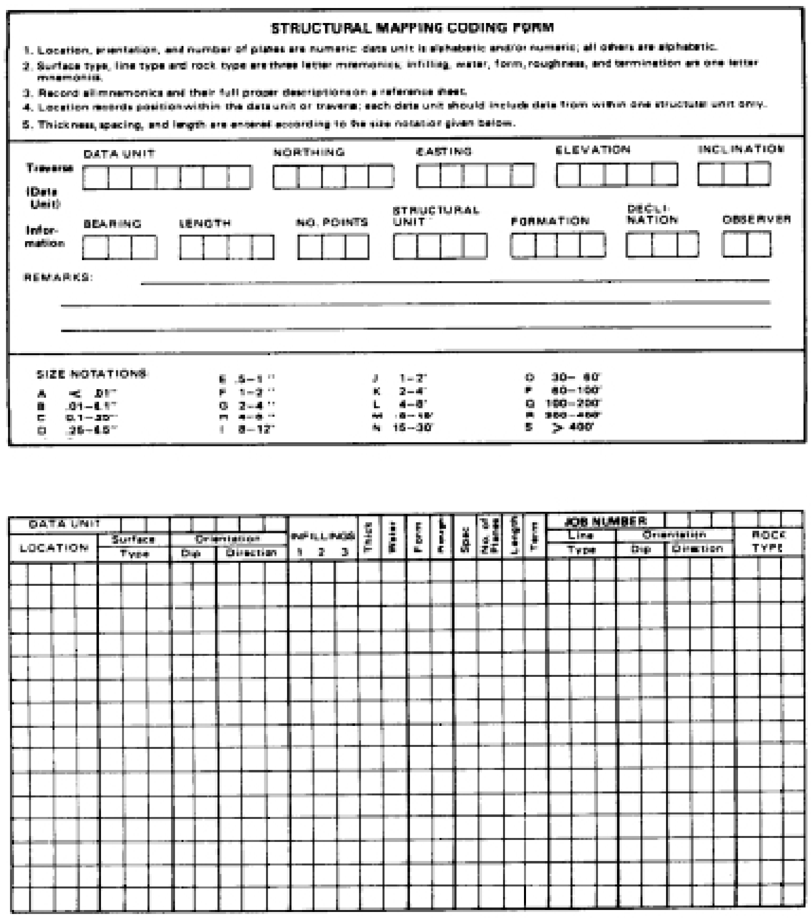
2.3 SERIAL NUMBER

The first time you run RockPack III for Windows, you will be asked to enter a serial number to unlock the software. For some demonstration versions, no serial number is provided so you may leave that field blank. If a serial number is provided, please be sure to enter that number in order to receive the full use of RockPack software.

3.0 DATA COLLECTION AND MANIPULATION

3.1 INTRODUCTION

The complete stability analysis of a rock slope depends upon a detailed survey of the orientations and characteristics of discontinuities within the rock mass. A discontinuity is defined as a structural weakness plane or surface along which movement of the rock mass might take place.



STRUCTURAL MAPPING CODING FORM

1. Location, orientation, and number of planes are numeric; data unit is alphabetic and/or numeric; all others are alphabetic.
2. Surface type, line type and rock type are three letter mnemonics; infilling, water, form, roughness, and termination are one letter mnemonics.
3. Record all mnemonics and their full proper descriptions on a reference sheet.
4. Location records position within the data unit or traverse; each data unit should include data from within one structural unit only.
5. Thickness, spacing, and length are entered according to the size notation given below.

Traverse (Data Unit) Information: DATA UNIT, NORTHING, EASTING, ELEVATION, INCLINATION, BEARING, LENGTH, NO. POINTS, STRUCTURAL UNIT, FORMATION, DECLINATION, OBSERVER

REMARKS:

SIZE NOTATIONS

DATA UNIT | LOCATION | Surface Type | Orientation Dip Direction | INFILLINGS 1 2 3 | Thick | Water | Form | Rough | Spac | No. of Planes | Length | Term | JOB NUMBER | Line Type | Orientation Dip Direction | ROCK TYPE

Figure 3.1a. Example of geologic structural mapping coding form (Golder Associates, 1981).

Types of rock discontinuities commonly encountered include fractures, joint sets, faults, shear zones, bedding surfaces, and foliations. A more complete listing of geologic structures related to rock slope stability is at the end of this chapter. Each discontinuity has characteristics such as length, orientation, spacing, surface roughness, physical properties of adjacent rock, infilling material and water conditions which relate directly to the likelihood of failure along that discontinuity. It is information about those discontinuity characteristics that goes into the field data files used in ROCKPACK III.

Field data files may be created either by writing data onto data collection forms in the field (Figures 3.1 a and b) and later entered into the computer or by collecting the data in a portable computer and uploading it to the main computer at a later time.

3.2 GENERAL DATA COLLECTION PROCEDURES

Discontinuity mapping is one means of systematically recording the characteristics of a representative sample of discontinuities in a rock mass. Although there are features common to all types of discontinuity mapping, there seem to be as many variations in philosophy and technique as there are slope stability experts. Discontinuities are sampled and mapped using procedures such as the following.

Line mapping - involves placing a 100-foot measuring tape along the slope face and recording data for every discontinuity that crosses the tape. Figure 4.1 illustrates examples of data sheets for line mapping. Included are measurements of position so that spacing may be statistically examined during computer analyses. The principal advantage of line mapping is the control that it imposes upon the collection of data for statistical purposes. A major disadvantage of line mapping is that it becomes tedious when large areas are mapped. It should be kept in mind that although much of the data are subjective in nature, they may be quite useful when analyzing potential failure surfaces.

Window mapping - all discontinuities falling within "windows" on the slope are examined. The author utilizes windows that are approximately 5' tall by 25' to 50 ' long with 10' to 25' between windows as permitted by site conditions. It is important to collect a statistically significant number of discontinuities in the windows and to use sound geological judgement when visually examining areas outside the windows for anomalous features. Window mapping has the advantage of being slightly faster than line mapping but has less statistical control.

> NOTE: The author prefers the following procedures whenever appropriate for line or window mapping. Before collecting data, walk the slope carefully examining the rock mass for general slope conditions and unusual features. This is a good time to make general written notes. It is always a good idea to photograph the slope. Select locations along the slope face for representative mapping. Place the measuring tape on the slope with nails driven into discontinuities as needed. It may be helpful to mark discontinuities with chalk (or paint if permissible) before mapping. As discontinuities tend to occur in similar sets, it is often convenient to record data for all discontinuities having similar orientations over a distance of 10 to 20 feet along the tape then return to the beginning of that section and repeat the process for other discontinuities.

Outcrop mapping - limited discontinuity data may be obtained from rock outcroppings in the vicinity of proposed excavations. These data usually compare favorably with data collected after excavation except for having less detail and less resolution of the clusters.

Oriented core logging - cores are sometimes used to obtain discontinuity data in areas where excavation has not yet begun. Some means of orienting the core with respect to its in-situ position must be utilized. Some parameters, such as discontinuity length and continuity are impossible to obtain from oriented core. Other parameters, such as infilling materials and water staining can be approximated.

Photographic mapping - photomosaics may be made and covered with clear plastic so that locations of discontinuities, changes in geologic nature, problem areas, and other significant features in a rock slope may be traced on the photos and annotated at the site. This should be done in addition to other mapping techniques where possible. It allows a record of both the window and non-window areas to be made. Photographs also are of help in documenting any changes that occur in the slope with time.

Today, digital cameras make if possible to take pictures, paste them together in a graphics program, and annotate them in a very short time.

Discontinuity # (3)
Traverse Trend (3)
Distance (2.1)
Rock type (1)
*Hardness (2)
Structure (2)
Zone width (2)
Joint spacing (2)
Dip Direction (3)
*Dip Value (2)
*Discontinuity Length (3.1)
*Continuity (1)
*Filling Type (3)
Thickness (1)
Filling Hardness (2)
*Water (1)
*Roughness (1)
Remarks

ROCKPACK DATA COLLECTION FORM

* Indicates parameter may be used in discontinuity significance index calculations.

Figure 3.1b. Field data collection form developed for use with ROCKPACK III.

3.3 ROCKPACK III DATA COLLECTION

Once the software is installed, you are ready to enter discontinuity field data or import data from RockPack I or II. RockPack III uses .csv, or "comma separated values" as its working format. Therefore, new data sets created within RockPack III will be saved as .csv files, and data files from RockPack I and II must be converted from .dat to .csv.

3.3.1 CONVERSION OF OLD ROCKPACK II DATA FILES

1. RockPack III easily converts older RockPack data sets to .csv data as follows:

2. Select the "**Enter Data**" icon, the leftmost button in the top toolbar (spreadsheet icon) in Figure 3.2a.

3. A "Data Entry Option" window will appear like that in Figure 3.2b below. Click "**Continue**." A blank data entry spreadsheet will appear similar to that in Figure 3.2c.

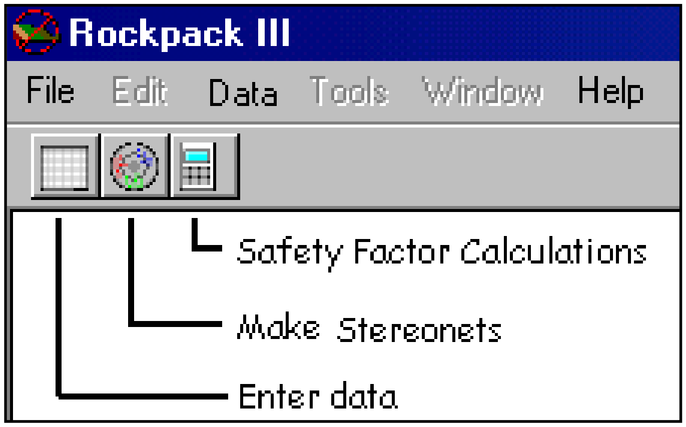


Figure 3.2a. Upper left desktop in RockPack III showing main program selection icons.

4. Click "**Data**" on the top menu bar above, and select "**Import RkPk**." Use the browse window that appears to locate the RockPack I or II data files (**c:\rkpk2-04\data** in most cases.)

4. Select the .dat file of choice and either double-click the file or click the "open" button.

5. The data file will be imported into the window. At this point, the user may edit the data; add to the data, or simply save the data utilizing the "**Data**" button on the menu bar. More data files may be "appended" to this by importing another data set without closing the now open data set.

6. Upon saving, the user will be prompted for a new file name.

   The .csv extension will be added automatically. You may also change the location of the saved file at this time.

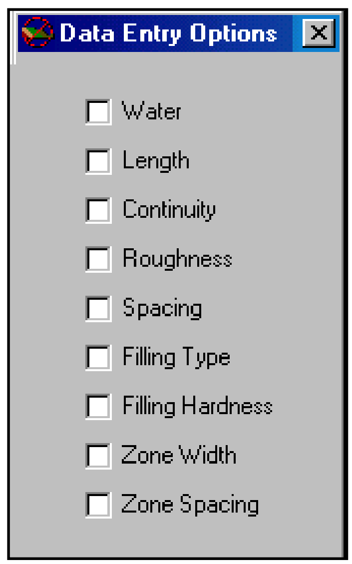


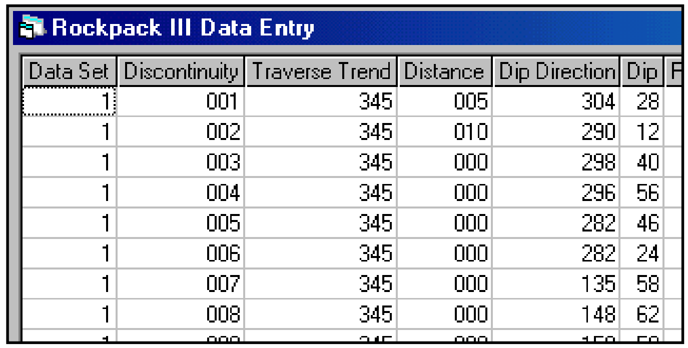
Figure 3.2b. Data entry parameter selection form.

3.3.2 CREATION OF NEW DATA SETS IN ROCKPACK III

Creation of new data files in ROCKPACK III is straightforward.

1. Select the "**Enter Data**" icon, the leftmost button in the top toolbar (spreadsheet icon) in Figure 3.2a above.

2. A "Data Entry Option" window will appear like that in Figure 3.2b above. Click "**Continue**" to choose the default selection of parameters to enter/view, or click "**Select All**" to enter data for all parameters, or click individually only those parameters that you wish to enter or view followed by "**Continue.**" A blank data entry spreadsheet will appear similar to that in Figure 3.2c.


Rockpack III Data Entry

Data Set	Discontinuity	Traverse Trend	Distance	Dip Direction	Dip	F
1	001	345	005	304	28	
1	002	345	010	290	12	
1	003	345	000	298	40	
1	004	345	000	296	56	
1	005	345	000	282	46	
1	006	345	000	282	24	
1	007	345	000	135	58	
1	008	345	000	148	62	

Figure 3.2c. RockPack III data entry spreadsheet.

3. Data may now be entered into the spreadsheet as per the column headers.

4. Once all data are entered, select "**Save**" from the **"Data"** pull down menu on the top menu bar.

5. This will bring up the save dialogue box, prompting you for a filename and location. The .csv extension will be added automatically.

6. The data file may now be used on stereonets to analyze for various potential rock slope failure types.

3.3.3 OPENING EXISTING ROCKPACK III FILES

1. Select the "**Enter Data**" icon, the leftmost button in the top toolbar (spreadsheet icon) in Figure 3.2a above.

2. A "Data Entry Option" window will appear like that in Figure 3.2b above. Click "**Continue**" to choose the default selection of parameters to enter/view, or click "**Select All**" to enter data for all parameters, or click individually only those parameters that you wish to enter or view followed by "**Continue.**" A blank data entry spreadsheet will appear similar to that in Figure 3.2c.

2. In the "**Data**" pull down menu on the top menu bar, select "**Open**."

ROCK SLOPE STABILITY ANALYSES EQUIPMENT CHECK LIST

Typical Radford University Projects

1. FIELD GEAR

( ) Hammer, compass, belt, handlens, clipboard, data sheets
( ) 100-ft measuring tape, nails, chalk, flagging, paint
( ) Backpack, rain gear, sample boxes/bags
( ) First Aid Kit, hard hats, safety vests, boots, cones/signs

2. CAMERA EQUIPMENT

( ) 35mm camera, different lenses, & film
( ) Polaroid camera, film, & plastic overlays
( ) Cassette recorder, microphone, tape, batteries
( ) VHS Camcorder, video tape
( ) Tripod

3. COMPUTER EQUIPMENT

( ) Hand-held computer for data collection, batteries/cables
( ) Laptop computer, printer, paper
( ) 2 Extension cords, multi-line adapters
( ) data collection and analysis software

4. DRAFTING EQUIPMENT

( ) Graph paper, stereonets, tracing paper, tape
( ) Bow pencil, bendable straightedge, engineer's scale
( ) Mechanical pencils, soft lead

5. TEST EQUIPMENT

( ) Field scales, buckets
( ) Tilt tester (cohesion & friction)
( ) Portable rock saw
( ) Schmidt hammer / pocket penetrometer

6. REFERENCES

( ) ROCKPACK/BACKPACK software manuals
( ) Hoek & Bray / FHWA Manuals
( ) Site plans, photos, reports

7. COMMUNICATIONS

( ) Vehicle 2-way radio
( ) Portable 2-way radios and spare batteries
( ) Celluar phone

Figure 3.2. Equipment used in rock slope stability field studies.

3.4 TYPICAL DISCONTINUITY DATA

Data Set Number, Line#(1) and Discontinuity Number, JNT#3.
This can be any single digit from 1 to 9 and is used to designate the particular map-ping area for which data are being collected at a site. A site may have several data set numbers, each for a different location on the site. The data set number must be non-zero. The joint number can have up to three digits and is used to count the individual discontinuities along a given mapping line. The number entered should into the data entry program of ROCKPACK III would therefore be a 4 digit number, the first number representing the data set number, and the next 3 representing the discontinuity numbers within that data set.

Traverse Trend, TRAV(3). This is the compass direction in which the traverse is proceeding at the position of the current discontinuity. By convention, mapping proceeds from left to right along the slope. If the rock slope is straight, then the mapping line will be straight and the Traverse Trend will be constant throughout the data set.

Distance, DIST(2.1).
This refers to the distance from the mapping line origin to the point where the discontinuity being examined intersects the line. The maximum of 99.9 feet (format: DIST(2.2)) is generally long enough for any detail line. If a greater distance is required, the slope investigator may start over with a distance of zero being equal to 100 feet. From that point on, it must be understood that the values recorded should have 100 feet added to them to obtain the actual values.

Structure Type, STR(2).
This refers to the type of geologic structure forming the discontinuity being examined. Table P-1 in the PRECAUTIONS AND DISCLAIMERS section of this manual describes the structures typically found in rock slopes. During the initial site reconnaissance, the slope investigator may identify and assign any input code number from 0 to 99, to discontinuity types found at the site and to use those numbers in response to the appropriate cells in the data entry program. For example, 1 may represent bedding surfaces, 2 may represent joint sets, and 3 may represent major faults. Alternatively, the investigator may wish to use the numbers from Table P-1 for consistency between all sites studied. It is primarily a matter of what will be most convenient when reviewing the collected data later.

Rocktype, RKTP(1).
During the initial reconnaissance, the investigator should walk along the slope making notes of overall slope characteristics and unusual features. If more than one rock type is present, he should make a numbered list of rock types so that numeric codes may be entered for rock type. The present data collection program permits a one-digit rock type identifier (0 to 9). Later programs may allow multi-digit identifiers so that a large standard list of rock types may be referred to for consistency between sites. On a recent project, the author reserved 1, 2, and 3 to represent carbonate rocks; 4, 5, and 6 to represent shales; and 7, 8, and 9 to represent sandstones that might be identified along the slope.

Hardness, HDS(2). The hardness of the material on either side of the discontinuity is important when estimating strength characteristics along the discontinuity. Figure 3.3 lists some easily performed tests for estimating hardness. The appropriate input code should be entered into the appropriate cell on the data entry program. If infilling material is present, then the hardness of the infilling material should be entered in its respective column. (Utilized in DSI analyses.)

			Approximate Range of Unconfined compressive strength	
Hardness Input Code	Consistency	Field Identification	Kg/cm^2 (Approx. $Tons/ft^2$)	psi
1	very soft	Easily penetrated several inches by fist	< 0.25	< 3.5
2	soft	Easily penetrated several inches by thumb	0.25-0.5	3.5-7
3	firm	Can be penetrated several inches by thumb with moderate effort	0.5-1.0	7-14
4	stiff	Readily indented by thumb but penetrated only with great effort	1.0-2.0	14-28
5	very stiff	Readily indented by thumbnail	2.0-4.0	28-56
6	hard	Indented with difficulty by thumbnail	> 4.0	> 56
7	extremely soft rock	Indented by thumbnail	2.0-7.0	28-100
8	very soft rock	Crumbles under firm blows with point of geological pick, can be peeled by a pocket knife	7.0-70	100-1000
9	soft rock	Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow of geological pick.	70-280	1000-4000
10	average rock	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single firm blow of hammer end of geological pick	280-560	4000-8000
11	hard rock	Specimen required more than one blow with hammer end of geological pick to fracture it	560-1120	8000-16,000
12	very hard rock	Specimen required many blows of hammer end of geological pick to fracture it	1120-2240	16,000-32,000
13	extremely hard rock	Specimen can only be chipped with geologic pick	> 2240	> 32,000

Figure 3.3. Guidelines for estimating hardness and input codes for soil and rock during field mapping (modified from Piteau, et al., 1980, Part G).

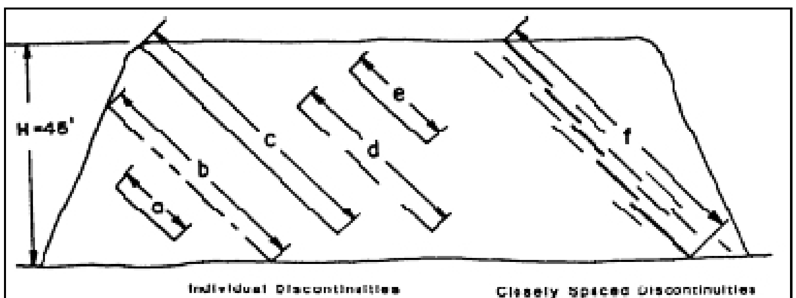
Dip Direction, DPDR(3). This is a 3-digit whole number from 0 to 360 indicating the direction in which the discontinuity being examined is dipping. This value may be found using a standard geologic compass such as a Brunton, but is most easily found using a mining compass such as a Clar Compass. It is important that dip direction not be confused with strike. Using a Brunton Compass, dip direction may be found by placing the flat surface of the open lid on the discontinuity and adjusting the com-pass until the circular bubble level is centered. If the compass lid is open more than 90 degrees, the dip direction is read from the north arrow. If the com-pass lid is open less than 90 degrees, the dip direction is read from the south arrow. Azimuthal compasses that read 0-360 degrees are better suited for this purpose than the traditional quadrant type Brunton Compass. It is often useful to place the open compass lid on a book to smooth out the discontinuity surface plus provide working space for the hinge if low dips are encountered.

Dip Value, DIP(2).
This is a 2-digit whole number from 0 to 90 indicating the degree of tilt of the discontinuity from horizontal. This value may easily be found using either a Brunton or a Clar Compass. (Utilized in DSI analyses.)

Joint Zone Width, JNZN(2).
Occasionally, the slope investigator may encounter a zone of discontinuities spaced so closely together that measurement of individual discontinuities becomes impractical. In that event, the investigator may begin by entering the distance to the center of the zone in response to the DIST prompt by the computer. Other prompts are treated in the usual manner. When the JNZN prompt is reached, the slope investigator enters the width of the zone, as intersected by the outstretched tape, rounded to the nearest whole foot.

Joint Spacing, JNSP(2).
Whenever the Joint Zone category is used, the Joint Spacing category should also be used to indicate the average spacing between the joints within the zone in whole inches. If the Joint Zone category is not used, the value for both categories should be 0. A value of 1 is used for spacings of 1 inch or less.

Discontinuity Length, JNLN(3.1).
The visible length of the discontinuity should be estimated as accurately as possible, without losing too much valuable time during mapping. Such estimates can be used for discontinuity comparisons aimed at discerning which discontinuities may be most significant to overall slope stability. The author generally makes visual estimates to the nearest 5 feet. (Utilized in DSI analyses.) Since visual length estimates are seldom accurate to the nearest foot, the digit to the right of the decimal point may be used to indicate the nature of the terminations of the discontinuity. See Figure 3.4. A ".0" may be used to indicate that terminations are not visible; that is, the discontinuity exits from the slope or disappears underground such that the ends are not visible, as is the usual case. A ".1" can be used to indicate that one termination is actually visible in the rock



Discontinuity	Length	Ends Visible	Continuity Input Code	Length Input Code
a	16'	both	1	16.2
b	45'	neither	2	45.0
c	60'	one	1	60.1
d	32'	both	3	32.2
e	21'	both	1	21.2
f	51'	neither	2	51.0

Figure 3.4b. Illustration of input codes for discontinuity length and continuity.

slope while a ".2" can indicate that both terminations are visible. A discontinuity could be given a JNLN of 6.2 to indicate a length estimate of 6 feet and to indicate that both terminations of this relatively short discontinuity are visible. Another discontinuity could be given a JNLN of 120.0 to indicate a visible length of 120 feet and that the terminations are not visible. The actual length may therefore be much greater. This information is useful in analyses that require knowledge of which joints are through going and which are not. Conservative rock slope analyses assume that the discontinuities are completely through going, in which case only an estimate of length is needed.

Continuity, CONT(1). This value represents an estimate of how continuous the potential failure surfaces are over the length assigned in the JNLN parameter and it is related to the origin of the discontinuity. Bedding planes and faults are almost always continuous over their lengths as a result of their modes of formation. Joints or fractures, on the other hand, may not have "popped" along their entire lengths in response to the stresses that caused them. Even a small percentage of intact rock along a discontinuity can significantly increase resistance to sliding. (Utilized in DSI analyses.)

DESCRIPTION	INPUT CODE
Zero % intact rock along discontinuity..................	1
Zero to 5% intact rock along discontinuity..............	2
Greater than 5% intact rock along discontinuity.........	3

Figure 3.4a. Criteria used to determine input codes for continuity as used in DSI equations.

This is not always an easy parameter to evaluate in the field, and it may require that a judgement be made as to whether a potential failure surface is likely to involve more than one discontinuity in a closely spaced set. Figure 3.4b illustrates the relationship between discontinuity length and continuity as used by the author. The discontinuities on the left side illustrate values that might be assigned to single discontinuities. A potential failure surface involving numerous closely spaced discontinuities is shown to the right. A continuity input code of 1 is the most conservative and will lead to high discontinuity significance values. It indicates that there is no intact rock along the visible length of the possible failure surface. This would be appropriate for bedding planes, fault zones, most foliations, and large joints and fractures. A value of 2 is used indicate that

0	Air (A) - total void exists between the walls of the plane.
1,2	Soil - Clay (C), sand (S)
3	Calcite (Z)
4	Detritus (D)' - debris washed into an open fracture.
5	Evaporites (E) - gypsum, halite, anhydrite
6	Feldspar (F) - hard, often pink, insoluble, good cleavages, easily weathered
7	Gouge (G) - wall rock is often ground up by movements along a fault zone. Gouge is the result of the accelerated weathering of the resulting fine grained materials; it is generally a green clay.
8	Breccia (B) - consolidated angular rock fragments larger than sand grains resulting from fault movement.
9	Ore (Ø) - valuable
10	Quartz (Q) - hard, white and insoluble

Figure 3.5. Common discontinuity infilling materials and their corresponding computer input codes (modified from Piteau, et al., 1980, Part G).

between 0 and 5% of the visible length of the potential failure surface consists of intact rock. A value of 3 indicates that more than 5% of the visible length consists of intact rock. Movement along the latter discontinuities is extremely unlikely and will lead to low discontinuity significance values.

Filling Type, FLTP(3).
Frequently, some additional material accumulates along the discontinuity surface. Figure 3.5 contains a list of the common infilling materials, each assigned a single digit identifier code. Up to three materials may be identified as occurring on the discontinuity surface. The more abundant infilling material should be represented by the digit farthest to the right in the input code. For example, a FLTP input code of 437 indicates that the most abundant infilling material is gouge, followed by calcite, with detritus making up the least amount. A value of 0 indicates that no infilling material exists.

Category	Degree of Water
1	The discontinuity is tight; water flow along it does not appear possible.
2	The discontinuity is dry with no evidence of water flow.
3	The discontinuity is dry with evidence of water flow, rust staining of discontinuity surface, etc.
4	The discontinuity is damp but no free water is present.
5	The discontinuity shows seepage, occasional drops of water, no continuous flow.
6	The discontinuity shows a continuous flow of water.

Figure 3.6. Subjective categories for classifying water conditions along a rock discontinuity from Piteau et al., 1980, Part G (generally not used with DSI programs).

Filling Thickness, FLTH(1).
The author utilizes uses the single digit to represent the width in tenths of an inch. The 0 represents a closed discontinuity and the 9 represents a filling .9 inches and greater. This procedure is satisfactory owing to the fact infilling material will tend to control stability when it is thicker than roughness irregularities of the discontinuities.

Filling Hardness, FLHD(2).
An estimate of filling hardness may be made, for the most abundant filling type, using Figure 3.5

Water Conditions, WTR(1).
A number of different techniques are popular for describing water conditions along the discontinuity surfaces. Figure 3.6 lists one set of guidelines. The author

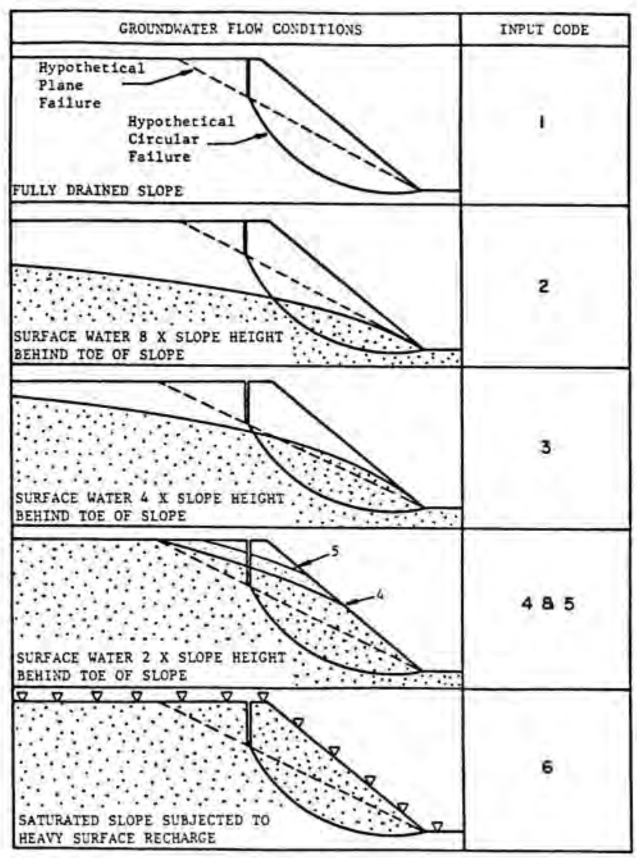


Figure 3.7. Computer input codes for discontinuity water conditions.

prefers to use a technique that can be directly related to potential water pressures. The WTR value entered depends upon how far up the slope water is seen to exit from the slope in the vicinity of the discontinuity. Figure 3.7 shows the positions used for estimates of WTR values, (utilized in DSI analyses.)

Roughness, RFNS(1).

A number of different techniques exist for estimating values of surface roughness in the field. One approach utilizes Barton's joint roughness coefficient (**JRC**). The coefficient is obtained by visual examination of the discontinuity surface and by comparison with Figure 3.8. The JRC value is used in Equation 3.1 below for shear strength. (Utilized in DSI analyses.)

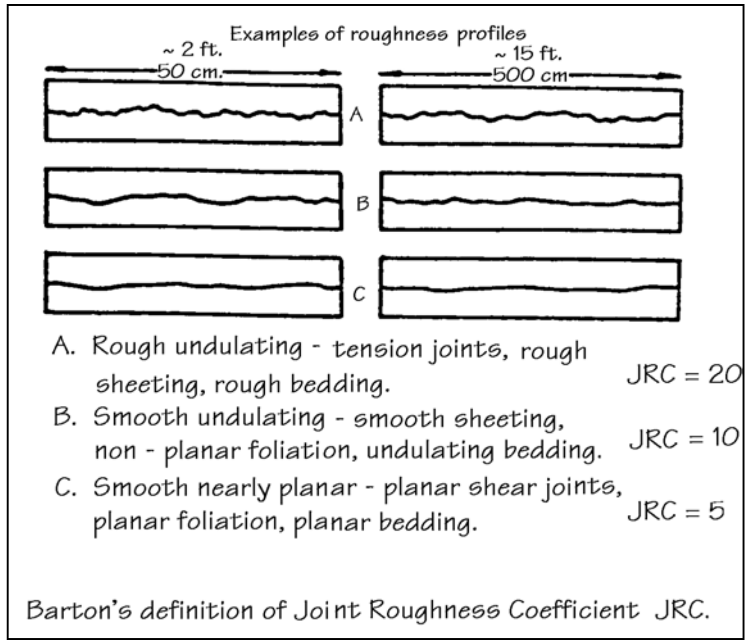


Figure 3.8a. Diagram for estimating Barton's Joint Roughness Coefficients (JRC). Modified from Hoek and Bray, 1981.

$$\tau = \sigma \text{ Tan } (\phi + \text{JRC Log } \sigma_j / \sigma) \quad \text{(eqn 3.1)}$$

The σ_j value represents the unconfined compressive strength of the material adjacent to the discontinuity and the value represents the normal stress on the discontinuity surface. It should be noted that Barton's equation provides considerably higher values of shear strength, for the low normal stresses encountered in most slopes, than does Equation 3.2 discussed below. This holds true even when the maximum recommended i value of 15 degrees is used in Equation in 3.2. The differences between the two equations are discussed further in Watts 1983.

Input Value	Remark
0	Discontinuity Filled
1	JRC ≃ 5
2	JRC ≃ 10
3	JRC ≃ 15
4	JRC ≃ 20

Figure 3.8b. Input codes for Joint Roughness Coefficients.

For use in DSI analyses, the author first makes an estimate of combined roughness and waviness in accordance with Figure 3.8a, which also lists approximate JRC values. The corresponding single digit code ranging from 0 to 4 is recorded. The DSI program later converts this code back to an approximate joint roughness coefficient. An entry of zero indicates that the discontinuity contains a significant amount of infilling material that will most likely control the shear strength.

Other approaches to evaluating roughness are not DSI-compatible but are presented here for completeness. Figure 3.9 illustrates the concept of different orders of roughness as projections on discontinuity surfaces. Figure 3.10, illustrates Patton's experiments involving shear strengths along regular projections, which resulted in Equation 3.2 for shear strength shown below.

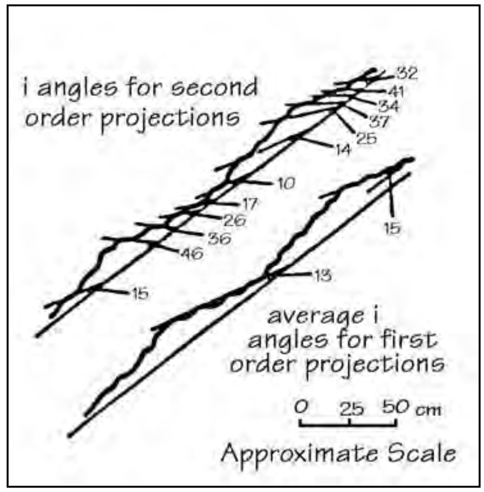


Figure 3.9. The concept of first and second order projections on discontinuity surfaces (from Hoek and Bray, 1981).

$$\tau = \sigma \text{ Tan } (\phi + i) \quad \text{(eqn 3.2)}$$

The terms in this equation are defined in Figure 3.10. Patton found that the equation agreed best with his field observations only when the first order roughness (or waviness) was used for *i* values. A maximum of 15 degrees has generally been accepted for *i*.

Neither Equation 3.1 nor Equation 3.2 accurately defines the situation if an infilling material is present. This is especially true if the thickness of the infilling material is greater than the size of the roughness asperities. Results, in that event, depend heavily upon the strengths of the infilling materials.

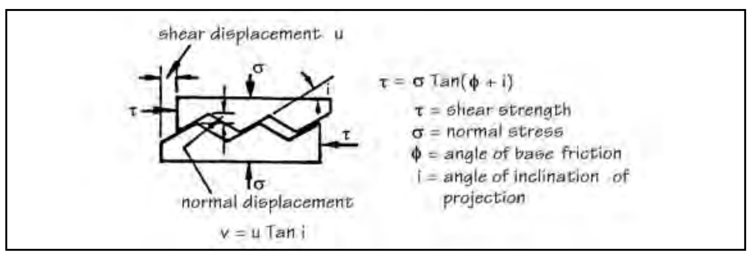


Figure 3.10. Definition of terms used in Patton's equation for shear strength involving projections on a discontinuity surface (from Hoek and Bray, 1981).

<u>Waviness, WAMP(2.1)</u>.

Two different procedures are common for describing the waviness characteristics of a discontinuity surface. One is to measure the interlimb angle (ILA) illustrated in Figure 3.11. A second is to estimate the wave amplitude as shown in Figure 3.12. The roughness data to be collected by a

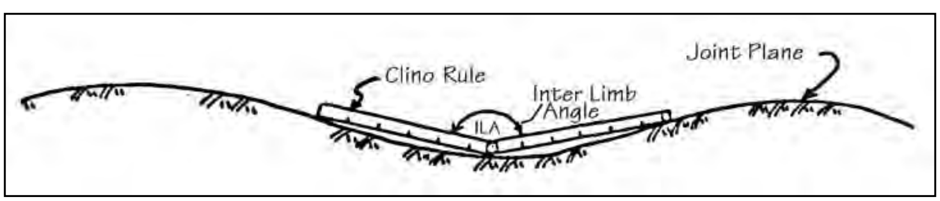


Figure 3.11. A technique for measuring the interlimb angle of discontinuity waviness (from Piteau, et al., 1980, Part G).

slope investigator, and the manner, in which it is to be collected, will depend in part upon the nature of the analysis to be performed. If one intends to use only Barton's equation, then Waviness and Wavelength need not be collected.

Wavelength, WL(3.1).
This is the final parameter related to discontinuity surface irregularities and is the average distance between "crests" of the irregularities. Wavelength is illustrated in Figure 3.12. Wavelength and waviness need not be collected if Barton's equation is utilized as in the DSI analysis.

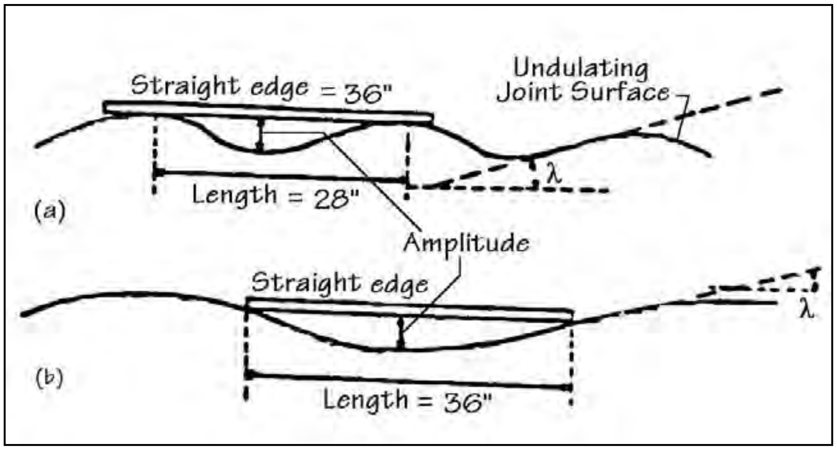


Figure 3.12. A technique for measuring wavelength and amplitude of a discontinuity (from Piteau, et al., 1980, Part G).

4.0 STEREONET ANALYSIS

4.1 INTRODUCTION

Stereonets permit the three-dimensional analysis of discontinuities within a rock mass. This enables the identification of discontinuities having unfavorable orientations in an existing rock slope or allows for the determination of optimum slope geometries during the design phase. Stereonet analyses are often referred to as kinematic analyses. Kinematics is the branch of dynamics that examines motion or potential motion without considering mass and force. Potential plane, wedge, and toppling rock failures may be identified kinematically on stereonets.

4.2 EXPLANATION OF STEREONET PROJECTION

A stereonet is the projection of planes and a 3-dimensional reference sphere through which they might pass, to a 2-dimensional representation. This allows the orientations of planes in space to be accurately represented and easily visualized as illustrated by Figure 4.1. There are several types of projections. The two projections most commonly used by geologists for structural analyses are the equal angle or Wulfe net, and the equal area or Schmidt net. The equal angle projection is used in structural geology when angular relationships between geologic structures, such as bedding planes are being examined. The equal area projection is most often used when the distribution of planes within certain areas of the reference sphere is examined. For a comprehensive discussion of stereonet projection, the reader should refer to Chapter 3 on graphical representation of geologic data, in the text by Hoek and Bray, 1981. A very brief discussion follows.

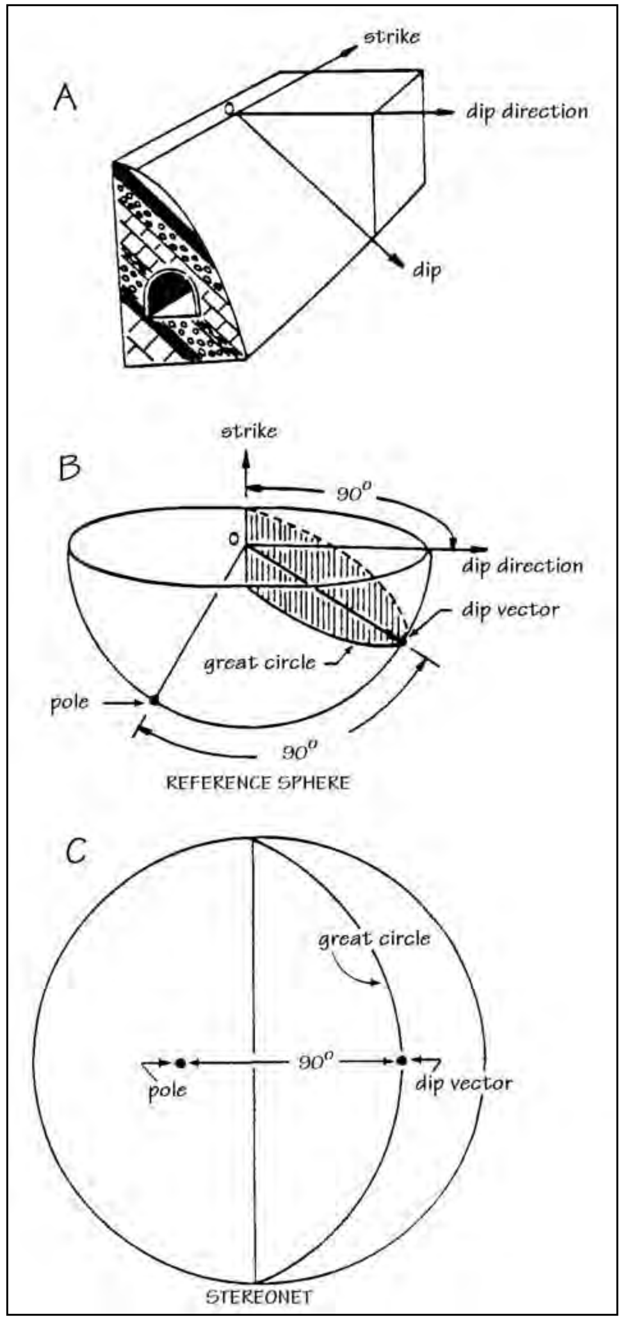


Figure 4.1. A) Perspective view illustrating strike and dip of bedding surface. B) Lower hemisphere illustration of 3 methods for representing a single plane in space. C) Stereonet projection of part B.

In stereonet analyses, discontinuities are assumed to be planar. There are three possible representations of a plane in space on stereonets. They are poles, dip vectors, and great circles, as illustrated in Figure 4.1.

Geologists have traditionally used poles to represent planes. A pole is formed by passing a line perpendicular to the plane through the center of the reference sphere. The point where the line intersects the lower hemisphere is the pole and is projected upward to the stereonet.

A great circle is formed by the intersection of the plane in space with the lower half of the reference sphere. The stereonet projection of this intersection is an arc called a cyclographic trace of the plane, but commonly referred to as a great circle (Marshak and Mitra, 1988).

The dip vector is a single point, like the pole, except that it is plotted in the direction of the dip. Simply put, it is the midpoint of the great circle representation of the plane. As such, it clearly depicts the dip direction and dip value of the plane in space. The closer it is to the center, the steeper the dip. One advantage of the dip vector is that, it enables one to rapidly visualize the orientations of planes in space with very little training.

Each of the representations has its own advantages and uses. Poles and dip vectors are used to represent individual discontinuities as single points, keeping the stereonet less cluttered than if large numbers of great circles are used. On the other hand, great circles are used to represent slope faces so that they stand out clearly and the relationships between them and the individual discontinuities may easily be examined. Also, great circles are useful when representing clusters in wedge analyses as described later.

4.3 DISCONTINUITY CLUSTER ANALYSIS

Unless a rock mass is severely fractured, several distinct clusters will be obvious when discontinuities are plotted. The orientations of discontinuities in a rock mass are related to its geologic history. Figure 4.2 is a pole plot of data from a site in the Appalachian Mountains of Virginia. The poles have been grouped into clusters by eye and numbered for identification. Figure 4.3 is a dip vector representation of the same data. Note the changes in relative position and appearance of each cluster in the two plots. Figures 4.4 and 4.5 show great circles being drawn representing these clusters. Discontinuity clusters are not always easy to identify by eye on a plot; hence, orientation data are sometimes contoured to make groups more obvious, sometimes contoured to make groupings

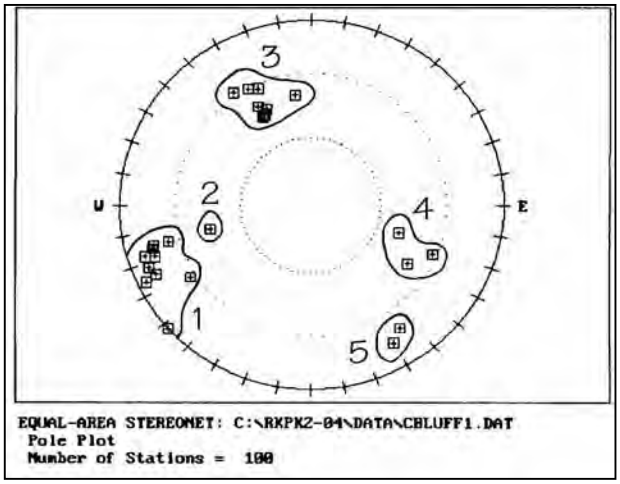


Figure 4.2. Pole plot of data from a site in the Appalachian Mountains of Virginia. The poles have been grouped into clusters by eye and numbered for identification (from RockPack II).

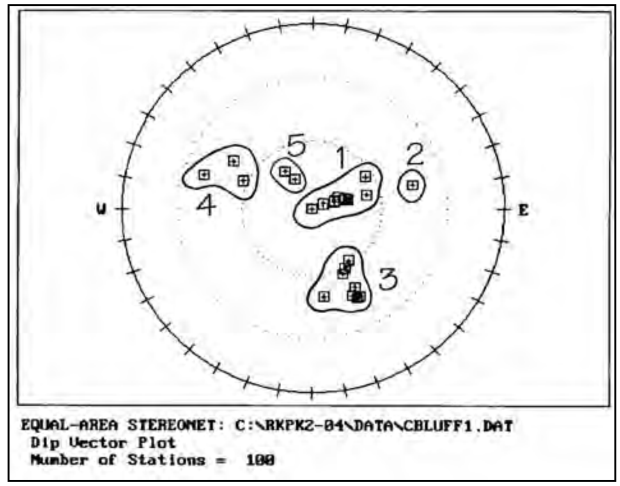


Figure 4.3. Dip vector representation of same data as 4.2. Note the differences in position and appearance of the clusters in the two plots (from RockPack II).

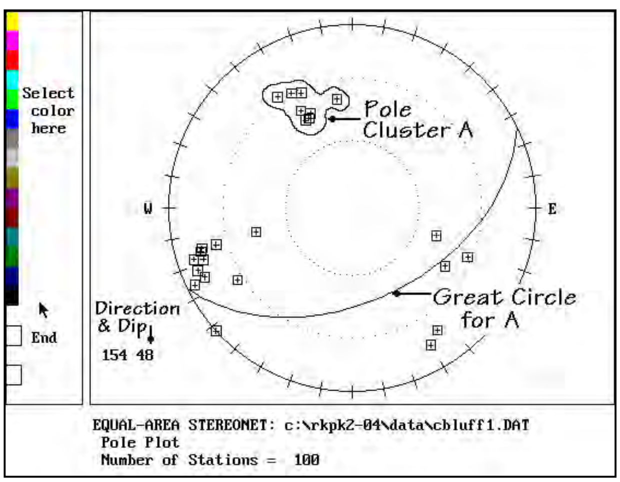


Figure 4.4. Great circle representation for poles of Cluster A (from RockPack II).

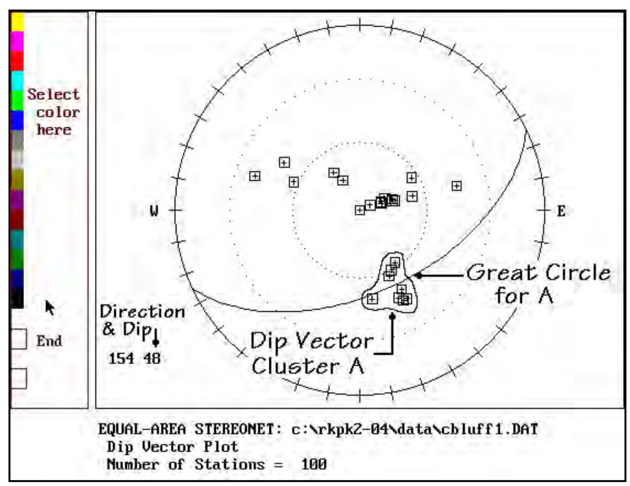


Figure 4.5. Great circle representation for dip vectors of Cluster A (from RockPack II).

4.4 STEREONETS IN ROCKPACK III

Stereonets in RockPack III are essentially the same as with previous versions; however, the graphics are much improved, and the ease of use has been enhanced tremendously.

4.4.1 SIMPLE STEREONET PLOT

To create a simple stereonet plot of a data set, click the middle icon on the toolbar (the Globe icon). Refer to Figure 3.2a.

1. If structure types have been defined during data entry, checking the "**Define Structures**" box will cause the structures to plot on the stereonet as symbols. Not checking this will result in all structures receiving the same symbol, regardless of type. Define structures is the default.

2. Click the **Open File** button; this brings up a dialogue box enabling the user to find and select a .csv data set file. (The user is referred to Chapter 3 for information on data collection and manipulation, as well as data conversion from older RockPack versions).

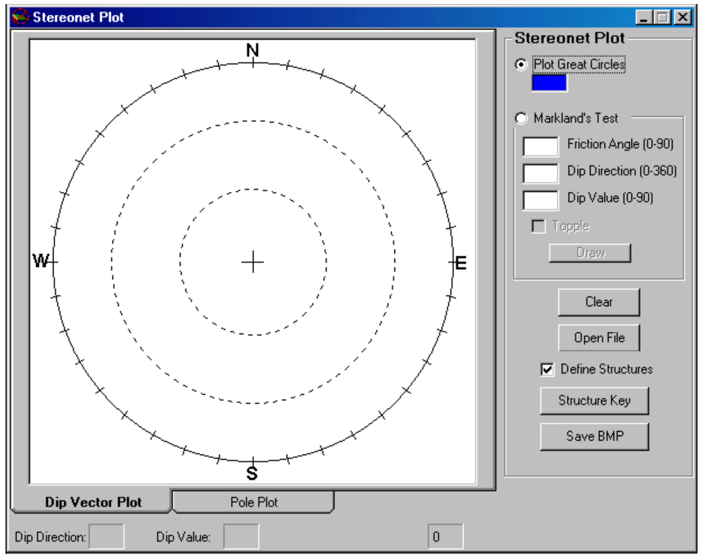


Figure 4.4.1a. Stereonet plotting screen in RockPack III.

3. Select the file, and click ok. The data will then be read and displayed on the stereonet plot. At any time, the user may press the "Save BMP" button, which captures the image, and saves it as both a Dip Vector Plot, and a Pole Plot. The letters "dv" and "pp" are automatically added to the file name to distinguish between the resulting files. The user may switch back an forth between Dip Vector plots and Pole Plots of the data set at any time by clicking on the appropriate tab beneath the stereonet.

4. Selecting the "Great Circles" radio button at the top of the window allows the user to select the color (click on the colored window), and then use that color to mark great circles on the stereonet with the mouse by clicking on the stereonet. As the great circles are drawn, the dip vectors are given at the bottom of the screen.

5. Markland's test may be performed, as defined below, by clicking the "Markland" radio button, and placing appropriate information in the blank fields. Clicking "**Draw**" at any time creates the Markland's Test Plot. Checking the "Topple" box and then selecting "**Draw**" adds the Topple Zone (see section regarding topple failures, 4.7) onto the stereonet.

4.5 EXPLANATION OF MARKLAND TEST THEORY

The basic concept of kinematic analyses for plane failure is straightforward. Two conditions must be met for sliding to occur.

First, the discontinuity must have a dip angle (θ) that is steeper than its friction angle (ϕ). In simple terms, the friction angle is the minimum dip angle for which sliding will occur along a discontinuity. For example, if two saw-cut slabs of rock are placed together horizontally and slowly tilted, the top slab will begin to slide when the sliding surface reaches the friction angle. Of course, this description ignores some obvious factors such as cohesion and irregularities between the surfaces, hence it is conservative. It is useful nevertheless. Actual friction angle values are obtained by performing direct shear tests on the discontinuities. Friction angles for a typical competent rock are around 28^o to 32^o.

The second condition for sliding is that the discontinuity must daylight from the slope face in a down-dip direction. This means that the discontinuity must dip in the same general direction as the slope face, but less steeply. Sliding cannot occur if the discontinuity dips back into the slope because it is locked in place. Sliding can only rarely occur if the discontinuity dips in the same direction but more steeply than the slope face, as it too is locked in. An exception to the latter case would occur if another less steep weakness exists (or develops) thus providing a pathway to daylight.

The two conditions described above can be represented on a stereonet in the form of a crescent-shaped critical zone (Figure 4.6). Discontinuity dip vectors, which lie within the critical zone, dip more steeply than the friction angle of the rock because they are inside the friction circle. They dip less steeply than the slope face because they lie outside the great circle representing the slope face. This is referred to as Markland's Test.

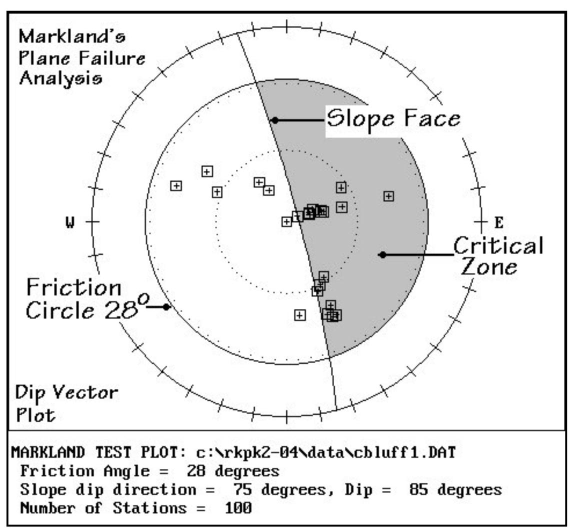


Figure 4.6. Markland's Test for plane failures using dip vectors.

Markland's test is an extremely valuable tool for identifying those discontinuities that could lead to planar failures in the rock mass and for eliminating other discontinuities from consideration. However, it should be remembered that not every discontinuity that plots within the critical zone will result in a failure. There are many additional factors that can affect stability along discontinuities. The user is referred to Chapter Ten on Discontinuity Significance Indices (DSI) for more information. The stereonet analysis is conservative owing to several assumptions that make the analysis possible.

To begin, all of the discontinuities are assumed to be continuous and through going, when in reality many of them are not. Even a small percentage of intact rock along a discontinuity can be enough to make it safe from sliding.

Also, the stereonet procedure is a "cohesion-equals-zero" analysis, in which the effects of cohesion are ignored. When this assumption is made, the fundamental limiting equilibrium equation for calculating safety factor reduces to (see appendix B)

$$\mathbf{FS = Tan\ \phi\ /\ Tan\ \theta.}$$

Therefore, whenever the dip value of the discontinuity (θ) is greater than the friction angle (ϕ), the safety factor is less than 1.0. Whenever the dip value is less than the friction angle, the safety factor is greater than 1.0 and the dip vector will plot inside the friction circle on the stereonet.

Finally, in recent years workers have noted that plane failures are not likely unless the discontinuity dips almost directly out of the slope face. The portion of the critical zone that lies within 20^o (plus or minus) of the slope face dip direction is considered most vulnerable. Outside of that 20^o zone, discontinuities disappear into the slope such that they often lock themselves in. Those discontinuities cannot be totally ignored; however, because other discontinuity sets may provide release surfaces, as in wedge failures.

4.6 WEDGE FAILURE - ANALYSES IN MARKLND

Stereonet analyses for potential wedge failures are similar to stereonet analyses for plane failure. In order for a wedge failure to occur, the line made by the intersection of the planes creating the wedge must plunge more steeply than the friction angle and less steeply than the dip of the slope face and in a direction such that it daylights from the slope face.

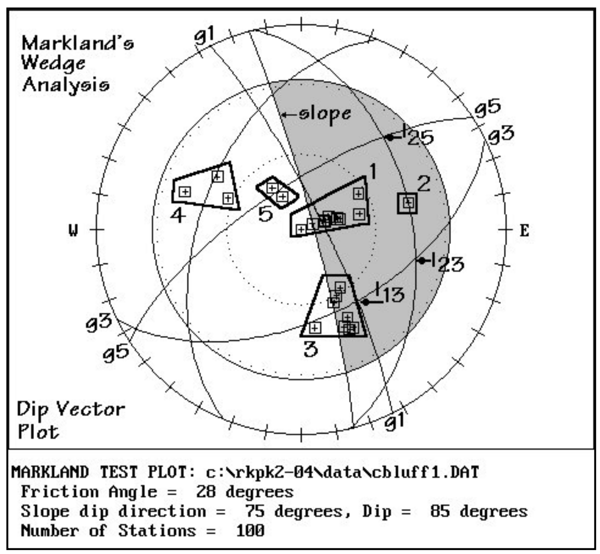


Figure 4.7. Markland's Test for wedge failures. Each great circle passes through the center of a dip vector cluster.

To test for these conditions, a single great circle may be chosen and plotted on the stereonet to represent the discontinuities of each cluster. If any of the great circles representing clusters on the stereonet intersect within the crescent-shaped critical zone then the conditions are met and a wedge failure is kinematically possible (Figure 4.7). The intersection point provides the plunge and trend of the line of intersection and is read from a stereonet in the same manner as dip and dip direction.

Selecting where and how the representative great circles should pass through the dip vector plots is a matter of debate, judgment and experience. The choice can profoundly affect the analysis. If the population of discontinuities is uniformly distributed within the cluster, the great circle should pass through the "center" of the cluster. If the density of dip vectors is greater in one part of the cluster, the representative great circle should be closer to that population center. Sometimes, contouring the stereonet can help clarify the situation. On the other hand, if some of the discontinuities in the cluster have greater significance, the great circle should pass closer to them as in Figure 4.8. The filled square in cluster #1 is a major fault, while the open squares represent short insignificant joints, hence the author chose a single great circle location weighted toward the fault. The cluster labeled #2 consists of uniform joints; hence a central location within the cluster was chosen.

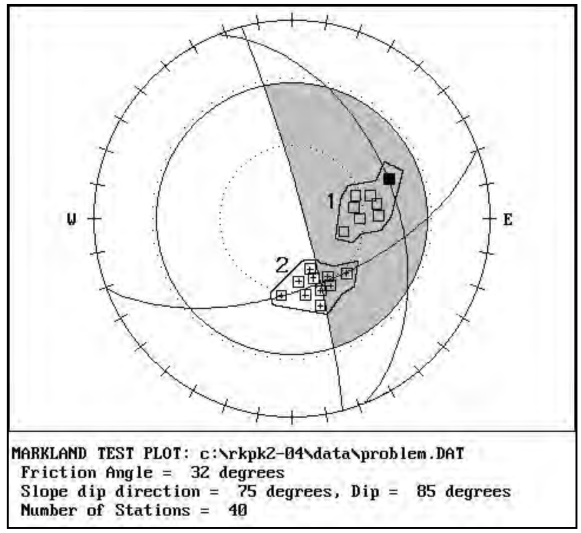


Figure 4.8. Selecting representative point in cluster by structure type.

A more realistic approach to kinematic wedge analyses is to select great circles that in some way "bound" the ranges of the clusters and provide a measure of all possible wedge intersections. Complex statistical programs exist which examine all intersection possibilities, however doing it graphically in ROCKPACK saves a great deal of time. Figures 4.9 (a-c) illustrate three ways to do this simply using the ROCKPACK II mouse-driven great circle option within MRKLND.

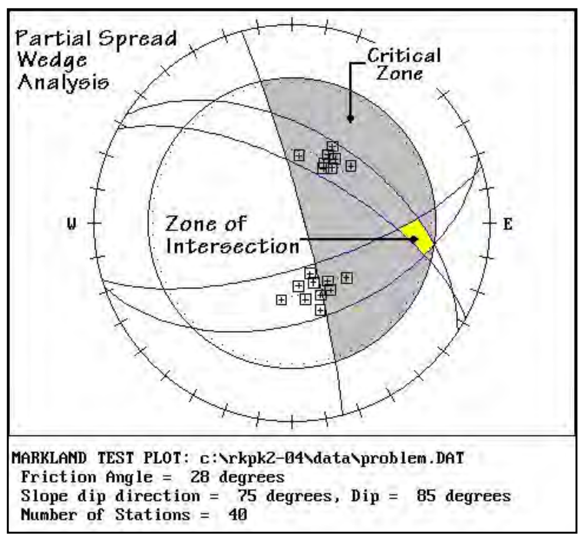


Figure 4.9a. Wedge bounding method a.

Figure 4.9a is the simplest. Two great circles bounding the inner and outer limits of each cluster were selected with the mouse. The result is a great circle "girdle" for each cluster rather than a single great circle. The intersections of the girdles are zones rather than points. If any portion of an intersection zone falls within the critical zone, then there are possible wedge failures among the discontinuities plotted. This is referred to as a partial spread wedge analysis as it does not fully cover all of the possibilities.

Figure 4.9b was created by clicking on every discontinuity found within the two clusters shown. It is referred to as the Spaghetti Plate Wedge Analysis because it begins to resemble a plate of spaghetti very quickly when many discontinuities are present. However, the range of intersections does more realistically portray all possible wedge failures.

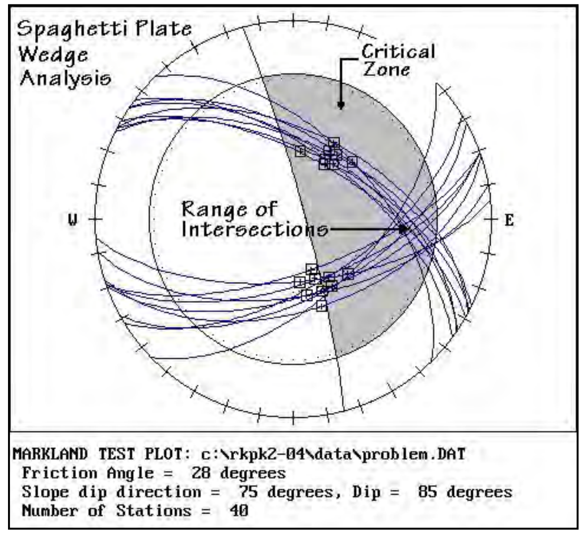


Figure 4.9b. Wedge bounding method b.

Figure 4.9c illustrates bounding each of the clusters with four great circles. Two bound the inner and outer limits as in 4.9a. The remaining two bound the radial limits, that is, the least and greatest dip directions. This is referred to as the full-spread analysis because it accurately portrays the full range of the intersection zone as in the spaghetti plate analysis but with fewer great circles. (Slight variations between Figure 4.9b and c are the result of slightly different data sets.)

Discontinuity Significance Indices (DSI, Chapter 10) can also play a role in understanding potential wedge failures. The wedge analysis of Figure 4.7 indicates that three wedge intersections representing three geometrically possible failures fall within the critical zone. Clusters 1 and 3 contain high DSI discontinuities and combine to form one of those critical wedges. Reexamination of the site revealed a wedge of that orientation within the rock mass, with tension cracks already forming along the crest. It failed in the spring of 1983. Sliding occurred along a Cluster 1 plane with a Cluster 3 plane acting as a release surface. The remaining wedge intersections do not involve high DSI discontinuities and have not resulted in rockslides within the mass.

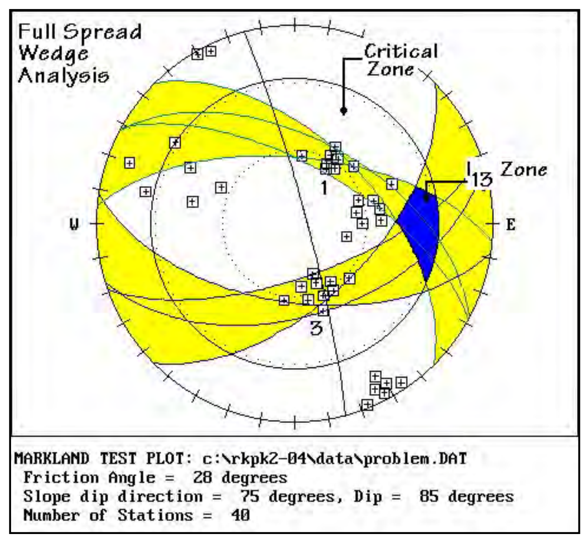


Figure 4.9c. Wedge bounding method c.

4.7 TOPPLING FAILURES - KINEMATIC ANALYSES IN MARKLAND

Goodman (1980, p265) discusses a stereonet procedure for kinematically identifying potential toppling failures. He states that interlayer slip must occur before large flexural deformations can develop. If the interlayer slip is controlled by friction angle o_j, toppling will occur if the normals to the toppling layers are inclined less steeply than a line inclined o_j degrees above the plane of the slope. The zone in which normals meet that condition is illustrated in Figures 4.10 a and b. In addition, toppling will occur only if the layers strike nearly parallel to the strike of the slope, typically within 30^o. Figure 4.10 b is a stereonet in which the shaded zone is the toppling critical zone for discontinuities plotted as poles.

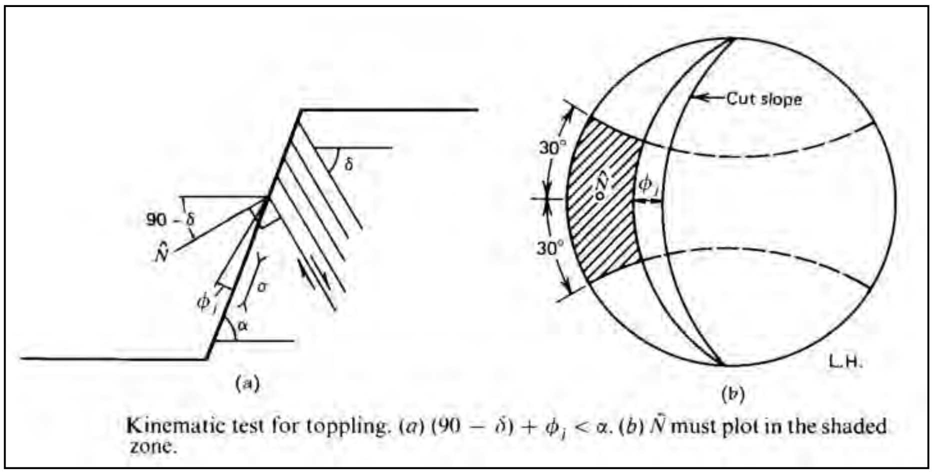


Figure 4.10 a and b. Kinematic analysis of toppling. From Goodman, 1980.

The RockPack programs favor the use of dip vectors over poles, hence Figure 4.11 illustrates the same toppling concept except the toppling critical zone is translated into its appropriate position for dip vectors. This screen diagram appears if T Topple is selected from the MARKLAND stereonet menu that follows the initial stereonet screen. Note that the author's interpretation of ∀30^o of dip direction from the slope face does not utilize the small circle projections as shown in Figure 4.10. The user is referred to any college structural geology text for discussions of stereonet projections.

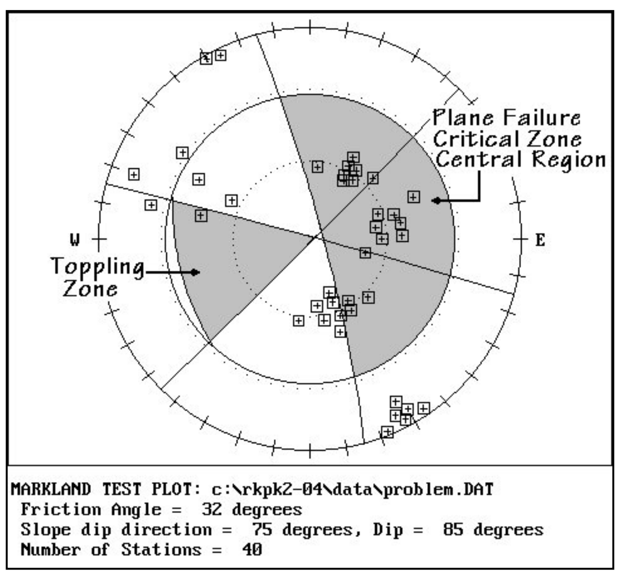


Figure 4.11. ROCKPACK II screen stereonet with topple zone for dip vectors indicated.

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USER'S MANUAL

ROCKPACK III for Windows
ROCK Slope Stability Computerized Analysis PACKage

PART TWO - SAFETY FACTOR CALCULATIONS

Created by

C. F. Watts, PhD, CPG
Engineering Geologist

in association with

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RockPack III

The complete rock slope stability analysis solution: from field data collection, to kinematic stereonet analyses, to safety factor calculations, to remediation.

Welcome to ROCKPACK III for Windows

These programs have been tested and are believed to be reliable engineering tools. No responsibility is assumed by the authors or the distributors for any errors, mistakes, or misrepresentations that may occur from any use of these programs. If not satisfied, purchaser may return materials within 30 days of receipt for refund.

Be sure to register !!

Be sure to register your software by mailing the enclosed registration form, or emailing your software serial number (located on your CD) along with your address and phone number to **cwatts@radford.edu** or **drgillia@radford.edu.** This will enable you to receive notifications regarding changes and upgrades.

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PART TWO - SAFETY FACTOR CALCULATIONS

5.0 OVERVIEW of SAFETY FACTOR CALCULATION PROGRAMS
(*PLANE, RAPWEDGE, CMPWEDGE* and *TOPPLE*)

RockPack III for Windows includes programs entitled: PLANE, RAPWEDGE, CMPWEDGE, and TOPPLE. These programs are used to calculate safety factors for potential failures identified by the user as being kinematically possible through stereonet analysis. The equations for evaluating plane and wedge failures are based on limiting equilibrium methods and come from Hoek and Bray (1981). The equations for evaluating toppling failures are based on sum of moments methods and come from Seegmiller (1982).

Starting the safety factor programs:

1. Click the third icon (calculator) on the RockPack III toolbar, as shown in Figure 5.1.1, or click on the **File** button and then **New**. Either method launches the Safety Factor Calculations window shown in Figure 5.1.2.

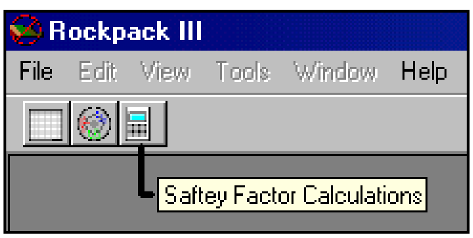


Figure 5.1.1.

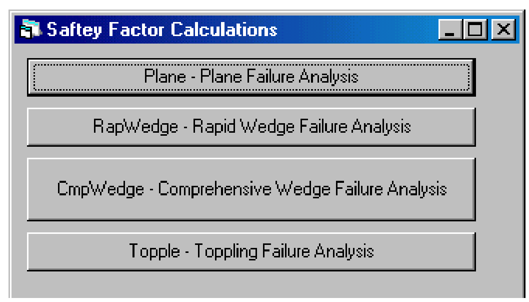


Figure 5.1.2.

2. Select the type of potential rock slope failure to be evaluated. The choices are **Plane,** for plane failure analyses; **RapWedge**, for rapid calculation of safety factors for simple wedge failures; **CmpWedge**, for more comprehensive analyses of potential wedge failures; and, **Topple**, for calculating safety factors of potential toppling failures.

<u>Note</u>: Chapters 6 and 7 from the old RockPack II User's Manual are no longer applicable. For numbering consistency, Chapters 6 and 7 are omitted here.

8.0 PLANE FAILURE ANALYSIS (PLANE)

8.1 INTRODUCTION

The program PLANE was developed to calculate the safety factor against translational sliding along discontinuities in a rock mass. It utilizes limit equilibrium theory and includes the effects of external loading, water pressures, rock bolt or cable forces and earthquake or blasting accelerations. PLANE should be used whenever discontinuities having unfavorable orientations have been identified, by field observation or by stereonet analysis, in order to evaluate the severity of the potential failures. PLANE is also useful in the design of artificial support systems by calculating safety factors resulting from various rock bolt or cable tensions and angles.

PLANE does not utilize the field data files, which are used in the stereonet programs, but requests appropriate slope parameters from the user. It provides the option of saving the parameters for later use, and calculates safety factors. PLANE is extremely useful for examining the sensitivity of safety factors to important slope parameters. The analysis may be easily repeated as needed, changing only one or two parameters for each run.

The majority of the parameters in the analysis relate to proposed or existing slope geometry. Other parameters relate to water conditions that have been observed or that might be expected. The strength parameters of cohesion (c) and friction angle (ϕ) are derived from Mohr-Coulomb theory and may be obtained by laboratory testing of samples. The values may also be approximated from reference tables or by simple field tests. The degree of accuracy required for the strength values will depend on the needs of the individual situation. When conservative analyses are acceptable, the cohesion is often assumed to be zero and the friction angle is often assumed to be 30-degrees. Friction angles for rock discontinuities can range from near zero to as high as 45-degrees, but typical values range from 28 to 32-degrees.

8.2 SAFETY FACTOR CALCULATIONS

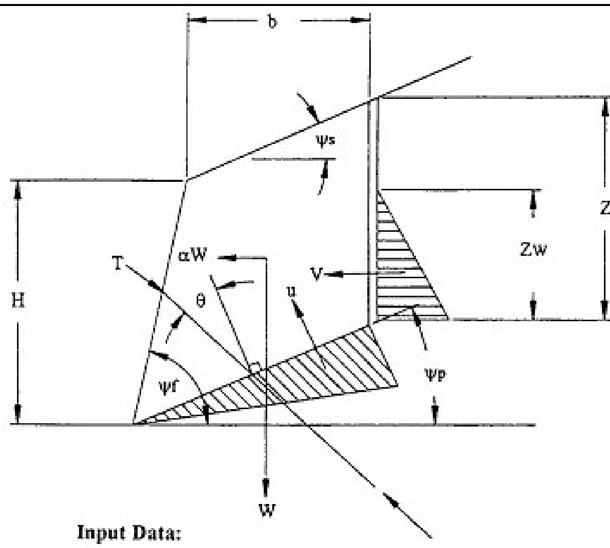
In limit equilibrium theory, safety factor is defined as the ratio of the resisting forces (F_r) to the driving forces (F_d):

$$\mathbf{FS = F_r/F_d}$$

When FS < 1, driving forces exceed resisting forces and failure is expected to occur. A safety factor of 1.3 is often considered the minimum acceptable value in rock slope work, although this may vary with site conditions. Obviously, sound engineering judgement is required.

The heart of RockPack plane failure analysis is the safety factor equation shown in Figure 8.2.1. For a more detailed explanation of limit equilibrium theory, and the derivation of the resisting and driving forces, the user may refer to Hoek and Bray (1981).

In the first paragraph of the chapter on wedge failures, Hoek and Bray note that plane failures are likely to occur along a discontinuity set only if the strike of the discontinuities is within 20 degrees of the strike of the cut slope. Otherwise, the discontinuities disappear into the rock mass at such an angle that another discontinuity set must be present, to act as a release surface, in order for failure to occur. In that event, wedge analyses such as RAPWEDGE or CMPWEDGE need to be employed.



Input Data:

- H = height of slope face.
- ψ_f = inclination of slope face.
- ψ_s = inclination of upper slope face.
- ψ_p = inclination of potential failure plane.
- z w/z = depth of water / depth of tension crack.
- α = horizontal acceleration due to earthquake or blast loading.
- T = tension of rockbolts or cables.
- θ = inclination of rockbolt or cable to normal to failure plane.
- c = cohesive strength of failure surface.
- ϕ = friction angle of failure surface.
- γ_r = density of rock.
- γ_w = density of water.
- ρ = parameter varied in sensitivity analysis.
- δρ = change in sensitivity parameter.
- b = distance of tension crack behind slope crest.
- A = surface area of sliding plane.
- W = weight of sliding block.
- u = uplift water force.
- V = water force perpendicular to tension crack.

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

Figure 8.2.1- Plane failure safety factor equation.

8.3 CONVENTION OF UNITS

The programs described in this chapter may be run utilizing either British Imperial units or those of the Systeme International. Whichever system is chosen, it is imperative that the convention listed in Figure 8.3.1 be followed.

A new feature in RockPack for Windows is the addition of a UNITS button on the toolbar. It allows the user to switch back and forth between British Imperial and SI units. The appropriate conversions are made automatically.

Type of Unit	Imperial	SI
Length	ft	m
Area	ft^2	m^2
Volume	ft^3	m^3
Force	lb(f)	kN
Pressure or Stress	$lb(f)/ft^2$	kPa
Unit Weight	$lb(f)/ft^3$	kN/m^3
Unit Weight of Water	62.4 $lb(f)/ft^3$	9.807 kN/m^3

SI Definitions:

kN = kiloNewton = 1000 Newton = 1000 kg m/sec^2
kPa = kiloPascal = 1000 Pascal = 1000 N/m^2 = kN/m^2
1 Newton = .1019 kg(f) of metric system

Determining Unit Weight from Specific Gravities:

Imperial Unit Wt = G x 62.4 $lb(f)/ft^3$
SI: Unit Wt = G x 9.807 kN/m^3

Figure 8.3.1- Convention of units to be followed in RockPack programs.

8.4 PLANE OPERATING INSTRUCTIONS

1. In the safety factor launch window (Figure 5.1.2), select PLANE.

2. The data entry screen (Figure 8.4.1) will appear. By selecting **View** in the menu toolbar, the user can have either a full-size screen, or a more compact screen utilizing tabs. Both formats incorporate the slope diagram as a visual aid and allow entry of the same parameters. When selected, each variable becomes highlighted in the diagram to assist the user.

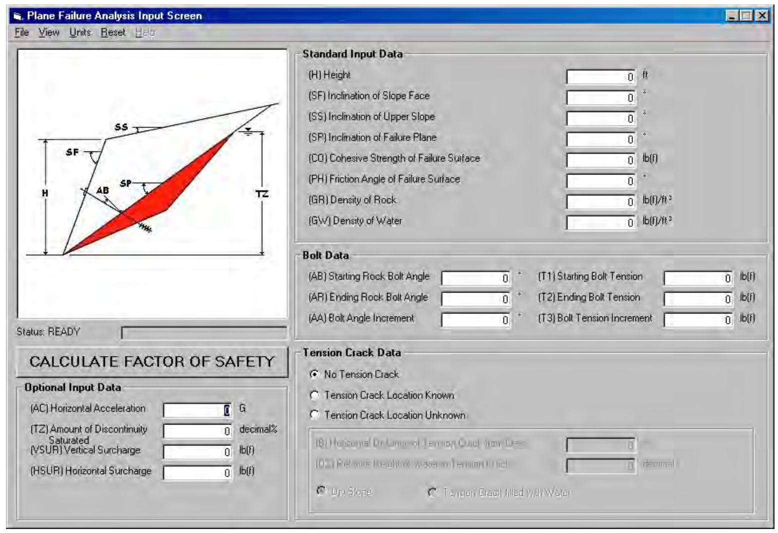


Figure 8.4.1. PLANE data entry window.

3. The letters that appear on the screen in parentheses next to the parameters are variable names used internally by the program and are normally of no significance to the user.

Following accepted practice for two-dimensional analyses, all calculations are for a unit section along the slope. In the British Imperial system, the unit section is one foot long (into the drawing). In SI measurement, the unit section is one meter long. It is especially important to remember this when entering rockbolt or cable tensions.

The following parameters may be entered:

- Slope height,
- Inclination of slope face,
- Inclination of upper slope surface,
- Inclination of potential failure surface,
- Horizontal acceleration due to blasting or earthquake (in G's, i.e., fraction of Earth's gravitational attraction),
- Tension in rockbolts or cables (see notes below),
- Inclination of rockbolt or cable to the normal to the failure plane (see notes below),
- Cohesive strength of the failure surface,
- Friction angle of the failure surface,
- Average unit weight of the rock in the slope,
- Unit weight of water in the appropriate units for the measurement system being used,
- Percentage of discontinuity or tension crack saturated with water in decimal form (see special notes below).

- -

NOTE #1: ARTIFICIAL SUPPORT

A. GENERAL

Bolt tensions are entered in lbs (or kN) and are in terms of a single force per horizontal foot (or meter) along the slope face. In reality, that single representative force will be distributed among a number of bolts in a bolting pattern.

The bolt angle used in these programs is measured from the PERPENDICULAR to the potential failure plane as shown in Figure 8.1. Often, it is desirable to know the angle of the bolt with respect to horizontal. The bolt angle from horizontal is easily found by subtracting the sum of the bolt angle (measured from the perpendicular) and the dip value of the failure surface, from 90-degrees. A negative (-) value for this bolt angle would indicate an upslope (above horizontal) orientation for the bolt. In some cases, analyses will indicate that the optimum angle for the bolt actually is above horizontal. However, in a practical sense it is not easy to place bolts above horizontal, owing to drilling rig limitations and the difficulties of keeping grout in the hole. As a result, an angle of 5-degrees below horizontal in conjunction with higher tensions and/or greater numbers of bolts is often used in those cases.

B. VISUALIZATION OF BOLT ANGLES AND TENSIONS

PLANE has provisions for visualizing the safety factors associated with a range of rock bolt angles and tensions. Figure 8.2.3 shows the output, which can be saved or printed by selecting **Print** from the toolbar. To utilize this feature, enter the starting bolt angle, the ending bolt angle and the increment through with the calculations proceed in each step. The starting and ending bolt tension and the tension increments are entered in the same manner.

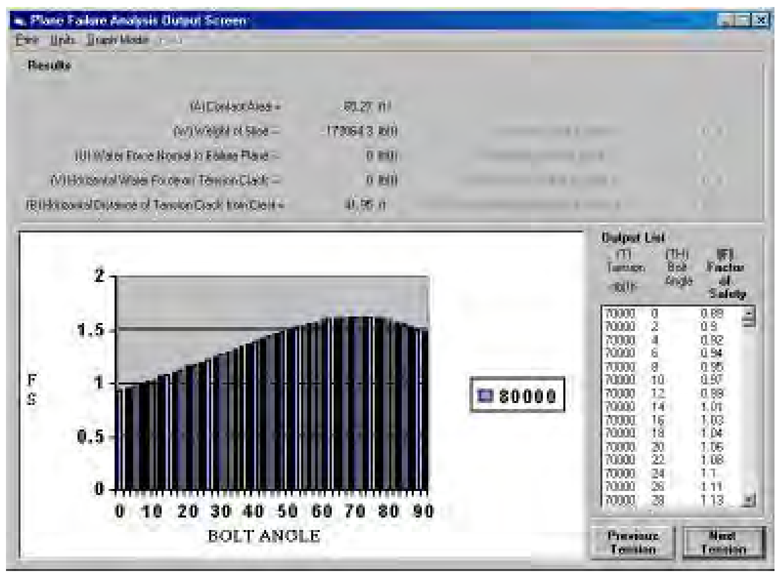


Figure 8.2.3. Factor of Safety output window, with bolt angle and tension information.

C. SINGLE BOLT ANGLE AND BOLT TENSION

If one wishes to analyze the slope for only one bolt angle and one bolt tension, then only starting values for angle and tension should be entered. Set ending values and increments equal to zero.

D. NO ARTIFICIAL SUPPORT

If one wishes to analyze the slope WITHOUT artificial support, simply leave all bolt parameters equal to zero.

- -

NOTE #2: WATER CONDITIONS

When answering the prompt regarding water in the slope, enter a value in decimal percent. A value of 0 indicates that the discontinuity is dry, .5 indicates that it is 1/2 full of water, and 1 means that the discontinuity is completely filled. In the case of tension cracks, the analysis assumes that the discontinuity is dry if the tension crack is dry. If there is any water in the tension crack, then the discontinuity is considered fully saturated. In all cases considered by this program, the discontinuity is free to drain from its lower end; that is, there is no obstruction to the flow such as might be caused by ice.

- -

(End special notes)

4. Enter values related to tension cracks. Choices for analysis are: no tension crack; tension crack location known; and tension crack location unknown. If the "location known" option is chosen, fill in the values regarding the HORIZONTAL distance from the slope crest to the tension crack. If the tension crack is below the slope crest, place a minus (-) sign before the distance value when entering it. Be sure that the value represents the horizontal distance to the crack and not merely the distance along the slope surface to the tension crack. If the "location unknown" option is selected, the computer will provide the worst possible locations for either the dry-slope case or the saturated-slope case, as directed.

5. In some cases, additional surcharges may be placed upon a portion of the slope in the form of buildings, walls, storage tanks, etc. Surcharges normally have only a vertical component; however, surcharges such as those resulting from an earth retaining wall along the crest of a rock slope may have also have a horizontal component owing to lateral earth pressures. To analyze the effects of a surcharge, fill in the appropriate values at this point in the program. **Keep in mind that any surcharge should be normalized for the unit slope type of analysis.**

6. The user then clicks the button "Calculate Factor of Safety". The output window with corresponding information below will be displayed (Fig. 8.2.3). The following parameters and calculated values are displayed:

- horizontal distance from crest to failure surface
- tension crack depth
- height of water in the tension crack
- failure surface contact area (per foot along slope)
- weight of sliding block (per foot along slope)
- water force normal to failure plane
- horizontal water force on tension crack
- calculated safety factor

7. The pull-down menus will list various options that may be chosen at this point depending upon the nature of the data. In any event, user will have the choice of printing results to the screen or to the printer, or starting over with new data, or saving the data set. Among the options are:

PRINT THIS SCREEN - allows the user to print the screen.

PRINT INPUT/OUTPUT DATA - allows the user print data and results.

PRINT INPUT/OUTPUT DATA TO FILE – saves output in a file.

PRINT CURRENT GRAPH – prints the bolt data.

Other options found in the output screen include methods for **editing the graph** format in a Microsoft Excel-like manner. The user may refer to the graphing sections of Excel to learn what each method entails. Right-clicking the mouse on the graph enables Excel functions to be selected, for choosing different graph types.

8.5 SAMPLE PROBLEM

The following data are from a highway rock slope in southwest Virginia: height = 95 ft; slope angle = 85 degrees; upper slope surface is horizontal (0 degrees); potential failure surface dips at 45 degrees; average unit weight of the rock is 165 pcf; and the unit weight of water is 62.4 pcf. There are no rockbolts or cables to take into account and horizontal accelerations will not be considered, although trains rumbling just beneath the slope have been noticed to create vibrations. The two major factors for which the stability sensitivity is to be examined are the strength parameters, cohesion and friction.

The strength parameters are best obtained by direct shear testing of samples along discontinuities. If no suitable test data are available, one may refer to charts based on past experience with similar slopes. One such chart is that shown as Figure 43 on page 114 of Rock Slope Engineering (Hoek and Bray, 1981) and is based on back-calculations of a number of failures. Using this chart, it is possible to bracket the probable strength values with upper and lower bounds. The cohesion value may range from 1000 to 2000 lb(force)/square ft, and the friction angle may range from 20 to 35 degrees.

For the first analysis, a low c value of 1000 psf and a low friction angle of 20 degrees were used, resulting in a factor of safety of .644. For the second run a higher value of c of 2000 psf and friction angle of 35 degrees were used. The resulting factor of safety was 1.26. Even with these high strength values, the safety factor is still less than 1.3, which is commonly required for highway work. Within these maximum and minimum values, the author's experience indicates that a c of 1400 psf and a friction angle of 35 degrees may be more likely for the site. This produces a factor of safety of 1.07. In this case, the slope is theoretically safe, but the safety factor is less than generally accepted.

9.0 WEDGE FAILURE ANALYSIS
(RAPWEDGE and CMPWEDGE)

9.1 INTRODUCTION TO RAPWEDGE

The program **RAPWEDGE** was developed to quickly calculate the factor of safety against translational sliding of a wedge created in a rock mass by two intersecting discontinuities, whose line of intersection daylights in the slope face. The solution is by limit equilibrium theory and is based upon equations presented by Hoek and Bray (1981). RAPWEDGE does not account for the influence of tension cracks, nor does it allow for the influence of external forces, both of which are accounted for in CMPWEDGE. RAPWEDGE does allow for different strength parameters and water pressures on each of the two discontinuity surfaces but it assumes that the slope crest is horizontal. In other words, the upper surface must dip in the same direction as the lower surface, or 180 degrees to it. The slope notation to be followed is shown in Figure 9.1 and the valid units are described in the previous chapter in Figure 8.2. The solution provides the option for either of the planes to be labeled 1 (or 2) and a check as to whether the planes form a valid wedge. The geometry of the wedge, and the nature of the water pressures on the discontinuity surfaces may cause contact to be lost on either or both of the surfaces. This possibility is accounted for in the solution.

9.2 RAPWEDGE OPERATING INSTRUCTIONS

1. As with PLANE, select the RAPWEDGE button from the selection dialogue box (Fig. 5.1). The following screen appears, with data input windows (Fig. 9.2.1)

2. The parameters that may be entered for analysis are listed on the screen. Those parameters include:

   - average unit weight of rock in the wedge,
   - height of slope crest above the intersection,
   - dip and dip direction of each plane (1 through 4), planes 3 and 4 MUST dip in the same direction,
   - cohesion and friction on planes 1 and 2,
   - average water pressure on planes 1 and 2,
   - unit weight of water in appropriate units.

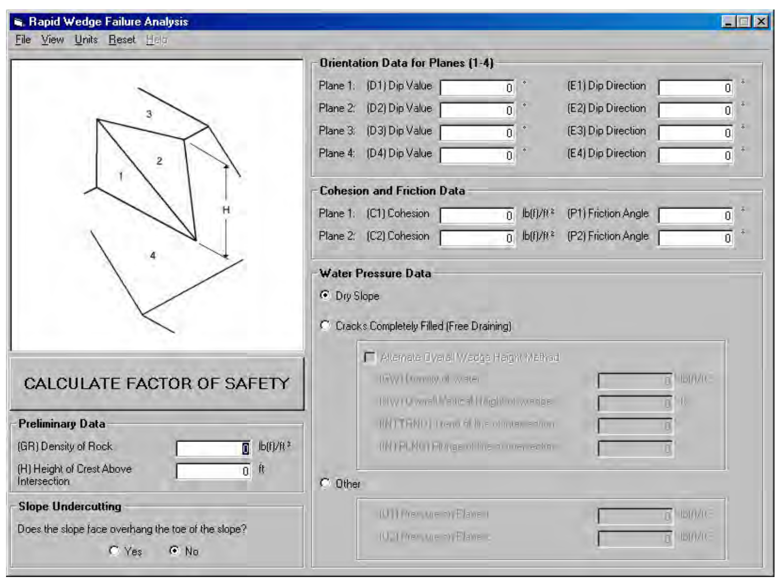


Figure 9.2.1. Data entry screen for RAPWEDGE

3. If the discontinuities are assumed to be saturated but free draining (no blockages to flow such as ice exist), then the water pressures on the two planes are

$$\mathbf{u_1 = u_2 = \gamma_w \ x \ H_{wedge} / 6}$$

where γ_w equals the unit weight of water in the appropriate units and $\mathbf{H_{wedge}}$ is the vertical height of the crest above the wedge intersection in the slope face. If the slope crest overhangs the toe of the slope, an index value, n, is assigned -1, otherwise it is +1.

4. The current value of each parameter is displayed in each entry cell. All values are initially set to zero. To change the value of a parameter, type in the new value and press <enter>. If a value is not to be changed, simply press <enter>.

5. The water pressure section provides the following choices: dry slope, discontinuities saturated but free draining, and other. If the "dry slope" option is selected, proceed to the next step. If the "discontinuities saturated" option is selected, the computer will prompt for the unit weight of water in the appropriate units and for the overall vertical height of the wedge (to calculate total head). If the upper slope surface is horizontal, this height will be the same as listed in instruction #2. Otherwise, it will be greater than that height. If the "other" option is chosen, values for the hydrostatic pressures on planes 1 and 2 will be needed.

6. In most cases, the slope crest does not overhang the toe of the slope. A notable exception might be a stream-cut or wave-cut cliff.

7. The computer now determines the nature of the wedge and the results are displayed on the screen by pressing the "Calculate Safety Factor" button. This will open a window such as figure 9.2.2, detailing the Factor of Safety information. The possibilities include: NO WEDGE FORMED; CONTACT ON BOTH PLANES; CONTACT ONLY ON PLANE 1; CONTACT ONLY ON PLANE 2; CONTACT LOST ON BOTH PLANES SO WEDGE FLOATS. The calculated factor

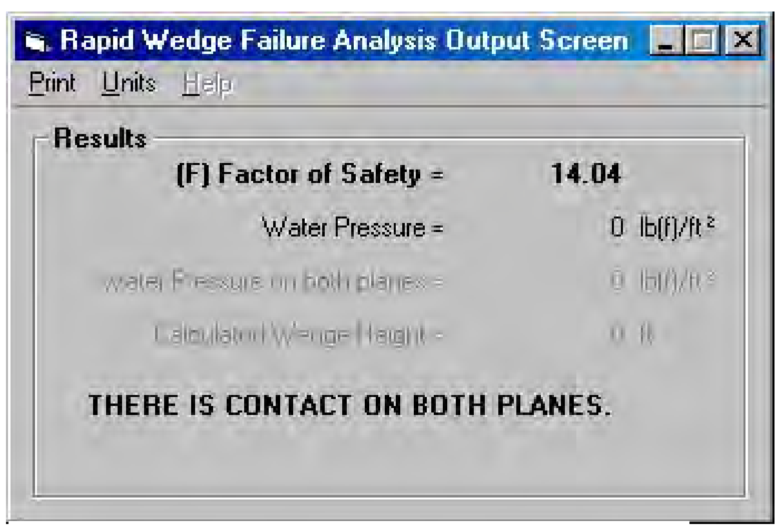


Figure 9.2.2. RAPWEDGE output screen

of safety for the slope is then displayed if appropriate.

8. The output may be printed as previously detailed in Section 8.

9.3 SAMPLE PROBLEM

Appendix 2 of Rock Slope Engineering by Hoek and Bray (1981) contains a sample problem, which may be solved utilizing the short version of the wedge analysis. The data for the problem are presented below.

1) dip/dip direction = 1) 47/052 2) 70/018 3) 10/045 4) 65/045,
2) average unit weight of rock in wedge = 25 kN/cubic meter,
3) height of crest above intersection = 20m,
4) cohesion on plane 1 = 25 kN/square meter,
5) cohesion on plane 2 = 0 kN/square meter,
6) friction angle on plane 1 = 30,
7) friction angle on plane 2 = 35,
8) water pressure on both planes 1 and 2 = 30 kN/square meter,
9) the slope crest does not overhang the toe,
10) water = 9.807 kN/cubic meter (from Figure 8.2).

Analysis of these values indicates that there is contact only on plane 1. Plane 2 therefore serves as a release surface. The factor of safety against sliding is 0.626. A slope thus constructed would be expected to fail.

It is interesting to note how the sensitivity of the calculated safety factor relates to water pressure. If the analysis is repeated, this time changing only the water pressure and setting it equal to zero for both planes, the factor of safety against sliding becomes 1.154. This is theoretically safe, even though it is somewhat below what might be desired.

9.4 INTRODUCTION TO CMPWEDGE

The comprehensive solution is similar to the short solution of RAPWEDGE, except that it is capable of evaluating a greater number of factors. The short solution would normally require about 30 minutes to calculate on a non-programmable calculator. The comprehensive solution would require some 4 to 5 times longer (Hoek and Bray, 1981). The solution is by limit equilibrium methods and is based upon equations presented by Hoek and Bray (1981). Both solutions may be obtained in just a few seconds on a microcomputer.

In addition to the parameters included in RAPWEDGE, the comprehensive analysis allows for the influence of a tension crack and for water pressure in the tension crack. Also, there is no restriction on the dip direction of the upper slope, which affects the inclination of the crest. Finally, the comprehensive solution has provisions for including the influence of external loading and cable tension. The notation to be followed is the same as found in the section related to CMPWEDGE.

Water pressures are given a great deal of consideration in this analysis. In cases where piezometric data for the discontinuity surfaces are not available, assumptions are made to produce conservative results. For example, the discontinuities may be assumed to be completely saturated. In such cases, the pressure is assumed to vary from zero at the free faces to some maximum value along the line of intersection of the failure surfaces. If no tension crack exists, the water pressures on the two failure surfaces, U1 and U2, are calculated as in RAPWEDGE. If a tension crack does exist, the pressures are calculated under the assumptions that the crack is completely filled with water, unless dry conditions are specified.

In view of the versatility of the comprehensive solution in CMPWEDGE, it may be used, in most cases, in place of both the Short Solution and the Plane Failure Analysis Program, which is a special case of the wedge analysis. Using all three programs and comparing results is an excellent means of cross checking analyses.

9.5 CMPWEDGE OPERATING INSTRUCTIONS

1. Select the CMPWEDGE button in the main menu as for RAPWEDGE. The data input window (Figure 9.5.1) appears.

2. The parameters that may be entered into the analysis are listed for informational purposes. The parameters are:

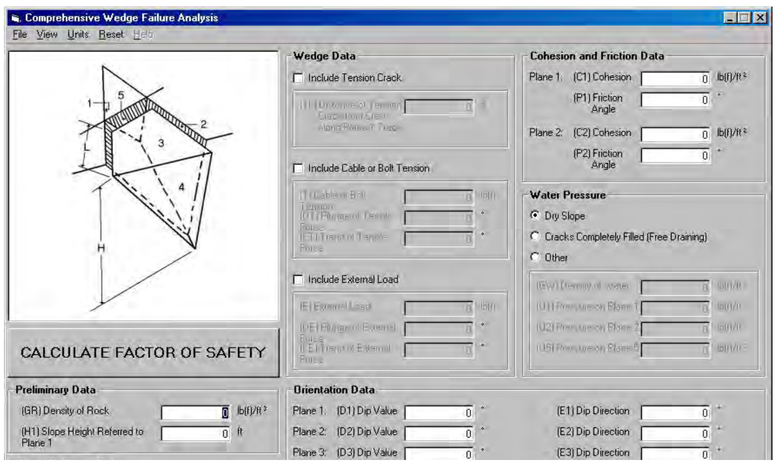


Figure 9.5.1. CMPWEDGE data input screen

- dip and dip direction of each plane (1 through 5 in Figure 9.2),
- height measured from the intersection of planes 1 and 2 to the intersection of plane 1 and the crest,
- distance of the tension crack from the crest measured along trace of plane 1,
- average water pressure on each face (may be calculated in the program),
- friction angle and cohesion on each failure plane, average unit weight of rock in the wedge, unit weight of water in the appropriate units, cable/bolt tension and external load (optional).

3. Enter parameter values as described above. The current value of each parameter is displayed along with the prompt. All values are initially set to zero. To change the value of a parameter, type in the new value. If a value is not to be changed, simply

press <enter>.

5. The data input section "INCLUDE CABLE OR BOLT TENSION?" is initially unchecked. If this is checked, the computer will prompt for the value of the tension in appropriate units of force, and then for the plunge and trend of the tension (similar to dip and dip direction but for force) by making the data entry boxes available.

6. The prompt "INCLUDE EXTERNAL LOAD?" is initially unchecked. If this is checked, the computer will prompt for the value of the load in appropriate units of force, and then for the plunge and trend of the load.

7. Fill in the values regarding cohesion and friction on planes 1 and 2.

8. The water pressure section provides input for the following choices: dry slope, discontinuities completely filled (but free draining), and other. If the "dry slope" option is selected, no further data will be required for this part. If the "discontinuities completely filled..." option is selected, the computer will provide spaces for the unit weight of water in the appropriate units. If the "other" option is chosen, the computer will prompt for the specific hydrostatic pressures on planes 1, 2 and 5. If no tension crack exists, the hydrostatic pressure on plane 5 should be zero.

9. Check the box regarding slope undercutting. In most cases, the slope crest does not overhang the toe of the slope. A notable exception might be a stream-cut or wave-cut cliff.

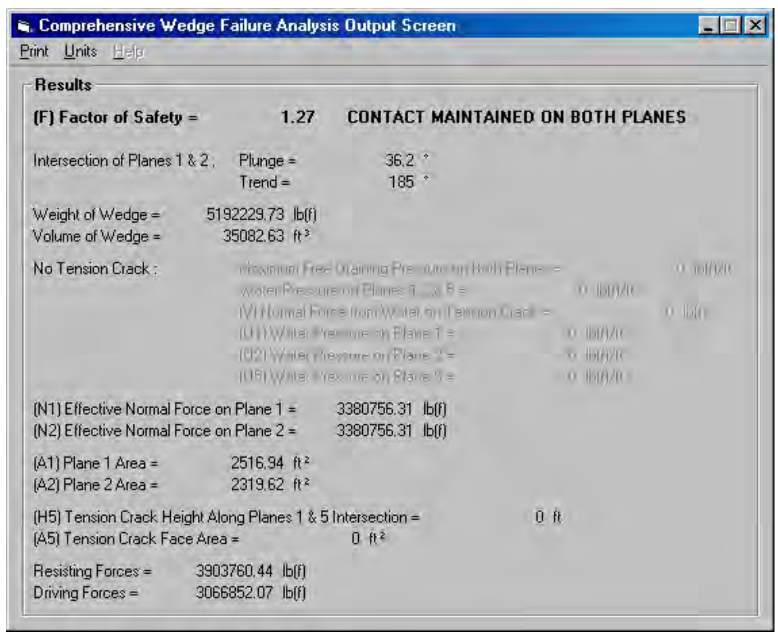


Figure 5.9.2 CMPWEDGE results output window

10. Click on the "CALCULATE FACTOR OF SAFETY" button, wedge geometry and safety factor results are displayed on the screen in a new window. The possibilities include: NO WEDGE FORMED; NO CONTACT ON PLANE 1 OR 2; CONTACT MAINTAINED ONLY ON PLANE 1; CONTACT MAINTAINED ONLY ON PLANE 2; CONTACT MAINTAINED ON BOTH PLANES. This information may be saved or printed by pulling down the menus and selecting the values most appropriate for the user.

11. The sensitivity of the analysis to various parameters may now be easily examined by

returning to the input screen. The analysis may be run through over and over again, changing one or two of the parameters each time.

9.6 SAMPLE PROBLEM

A sample problem for the Comprehensive Solution is provided on page 348 of Rock Slope Engineering (Hoek and Bray, 1981). The data are:

1. dip/dip directions for each plane =
   1) 45/105 2) 70/235 3) 12/195 4) 65/185 5) 70/165,
2. height referenced to plane 1 = 100 ft,
3. distance to tension crack from crest along 1 = 40 ft,
4. cohesion on plane 1 = 500 lb(f)/square ft,
5. cohesion on plane 2 = 1000 lb(f)/square ft,
6. friction angle on plane 1 = 20,
7. friction angle on plane 2 = 30,
8. average unit weight of rock in wedge = 160 lb(f)/cubic ft,
9. discontinuities in slope are assumed saturated.

The analysis of these data indicate that the wedge and tension crack are valid, contact is maintained on both planes 1 and 2, and the factor of safety against translation sliding of the wedge is 1.1387. Due to uncertainties in strength parameters, the safety factor should be rounded to 1.14. This is less than the usually accepted minimum of 1.3 for highway work.

The sensitivity of the safety factor to water pressure may now be briefly examined. If all parameters are kept constant, except for assuming a dry slope, the factor of safety becomes 1.7360 that rounds to 1.74. The slope would therefore meet the requirements, if it could be kept drained.

10.0 NUMERICAL ANALYSES OF TOPPLING FAILURES (TOPPLE)

10.1 INTRODUCTION

The topple option in the program provides a graphical indication of whether or not toppling failures are kinematically possible. The TOPPLE program described here provides a more quantitative way to examine potential topples once they have been identified. For additional information on these quantitative analyses, the user is referred to Seegmiller, 1982, pp. 273-277.

Three options are provided:

1. The first option calculates the **sum of the moments** of the potential topples. This is used in a manner similar to the safety factor concept (translational failures) to provide a measure of the degree of instability as shown in Figure 10.1. In the toppling case however, a sum of moments equal to **0.0** indicates a block at equilibrium. In the translational sliding case, a safety factor of **1.0** indicates a block at equilibrium. Also, safety factor calculations are **unitless** since they are the result of a ratio of forces; however, the sum of the moments will have units of distance x force (for example, **foot-pounds** in the British system).

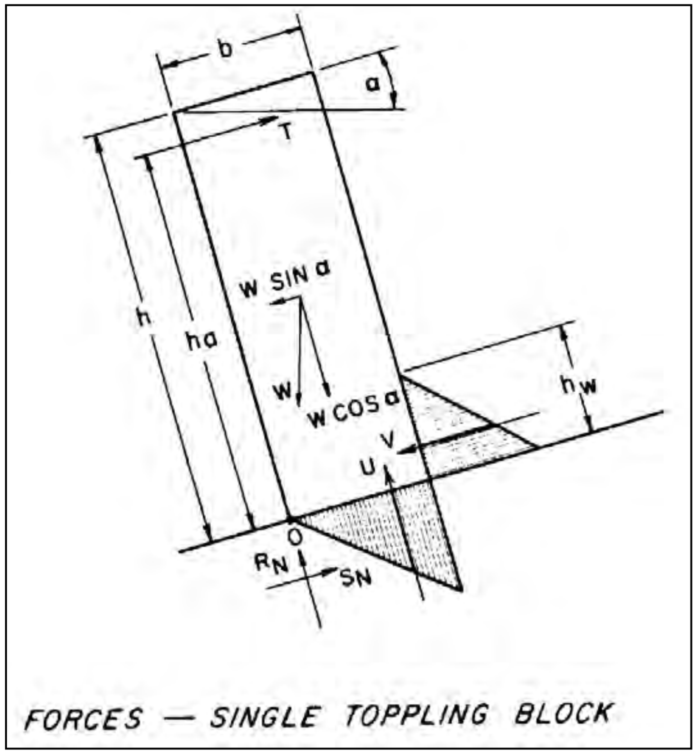


Figure 10.1. Resolution of forces in a toppling rock block, from Seegmiller, 1982.

2. The second option calculates the total restraining force necessary to prevent toppling of a single block by use of a rock anchor.

3. The third option calculates the thickness of rock blocks that if bolted together would alter the toppling geometry sufficiently to prevent the topple from occurring.

10.2 ANALYSES OF POTENTIAL TOPPLING FAILURES

In a toppling situation, a sum of moments equal to **0.0** indicates a block in equilibrium (the overturning moment is exactly equal to the resisting moment). A positive sum of the moments indicates a toppling failure is likely (overturning moment is greater than resisting moment). A negative sum indicates that the topple is not likely (overturning moment is less than resisting moment).

The following is taken from Seegmiller, 1982.

The toppling mode of slope failure is a very complex mode to accurately model. Many actual field problems have numerous factors that markedly deviate from the conditions that must be assumed in most models. For purposes of demonstrating how such a failure mode may be artificially supported, a very simple and restricted model is presented. The model is shown as Figure 10.1 and has the following qualifying assumptions:

1. The block is fixed at its lower downhill corner such that it cannot slide down the plane. Rotation or toppling around the point "O" is the only movement permitted.

2. The reaction force, R_N, is a point force and is acting at the point "O" at the beginning of rotation or toppling.

3. A column of water (may) exert a thrust force, V, on the uphill side of the block and it may be approximated by a triangular force distribution.

4. The column of water (if present) causes an uplift force, U, on the base of the block, which is maximum on the uphill edge and decreases to zero on the downhill edge. It may be approximated by a triangular force distribution.

5. Anchor force, T, (may be) applied normal to the block and some fixed object exists upslope to which the anchor (may be) attached. (Such analyses are based on the forces per unit slope concept)

10.3 REMEDIATION OF POTENTIAL TOPPLING FAILURES

The author's preference for REMEDIATION of potential toppling blocks is to remove the threatening blocks. As that is not always possible, the TOPPLE program provides for two types of remediation.

BOLTING IN PLACE: The force, T, in Figure 10.1 illustrates a remediation in which a potential toppling block is restrained by a counteracting moment in the form of a rock bolt placed a distance, h_a, up from the base of the topple block. A tension force calculated in this program option provides a sum of moments equal to zero (exactly equilibrium) and is per unit length (one foot in the British system) of block along the slope. A larger T value should be applied in order to exceed equilibrium conditions.

FASTENING BLOCKS TOGETHER: Topples sometimes occur when sets of joints exist (parallel to h in Figure 10.1) which free multiple blocks. The block farthest downslope generally must topple and leave the vicinity before the next block upslope will topple. If the block thickness, **b**, can be increased by bolting multiple blocks together, the toppling nature of the rock mass can be eliminated. However, the slope must still be analyzed from the standpoint of a possible translational plane failure along the lower block boundary.

10.4 TOPPLE OPERATING INSTRUCTIONS

The TOPPLE program is started by selecting TOPPLE in the RockPack III Safety Factor Window. The opening menu in the TOPPLE option will ask which of the three procedures you wish to use:

Choice 1 will calculate the Sum of the Moments for the block parameters you establish.

Choice 2 will calculate the tension required to bolt a single block in place providing a sum of moments equal to zero (a negative sum of moments is actually desirable here hence a greater tension should be used).

Choice 3 will calculate the thickness of blocks to bolt together to prevent toppling providing a sum of moments equal to zero (a negative sum of moments is actually desirable here hence a greater thickness should be used).

Entering the data requested into the boxes and pressing "Calculate" will generate the data at the bottom of the input window. The pull down menus provide various options, including saving, printing, etc.

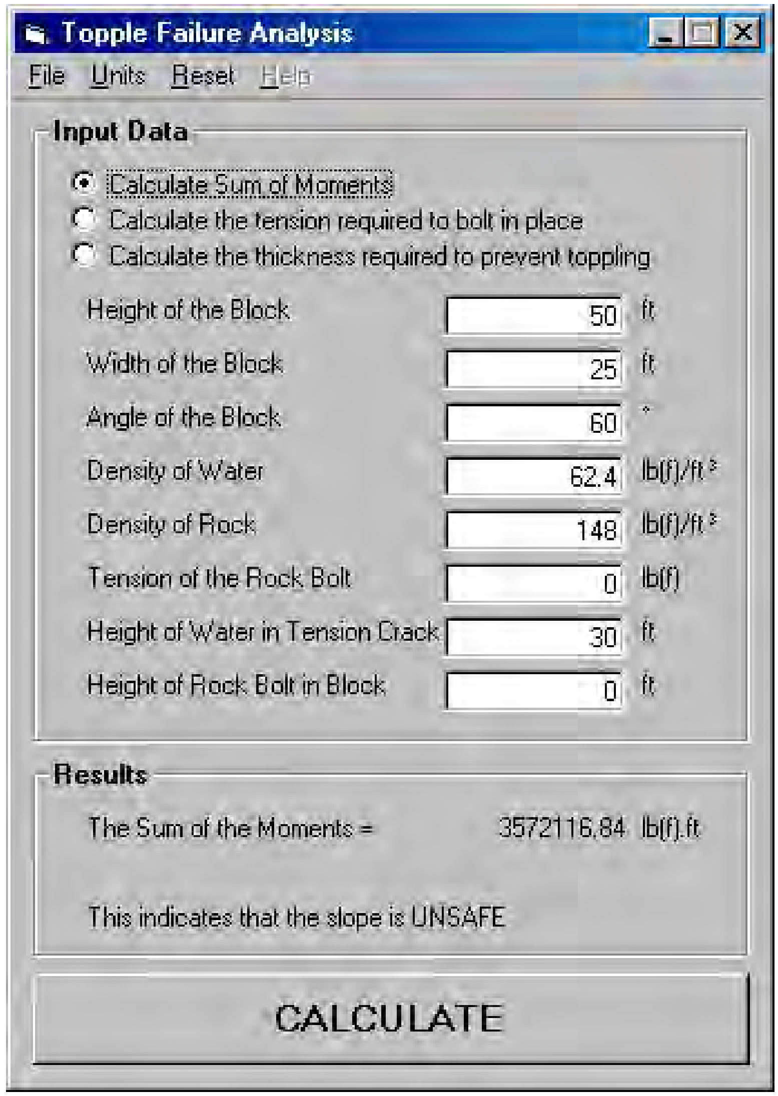


Figure 10.2.1-Topple data entry screen

A P P E N D I X A

EXERCISE ONE

An Introduction to Rock Slope Stability Analysis by Stereonet

The ROCKPACK II User's Manual is written under the assumption that users are already knowledgeable and competent in standard rock slope stability analysis methods. This Appendix is included simply as a refresher. For more detailed information on rock slope stability theory, please refer to the references listed.

ROCK SLOPE STABILITY ANALYSIS BY STEREONET

SECTION I. INTRODUCTION

Landslides represent a significant and widespread geologic hazard. Reports of various government agencies indicate that losses to buildings alone in the United States exceed $400 million per year and that more than $100 million per year is spent repairing landslide damage to highways and roads. Total economic losses from landslides in the United States are conservatively estimated to be in excess of $1 billion per year (Schuster and Krizek, 1978).

Much of the total landslide damage is attributable to failures of rock slopes. The stability of a rock mass depends on the orientations and characteristics of weaknesses in the rock called **discontinuities**, and generally **not** on the strength of the rock itself. Excavations made in rock during construction expose discontinuities which include such geologic structures as bedding planes, foliations, joints, and faults.

Rock slope failures can be quite catastrophic. All mountainous states, including Virginia, New York, California, Colorado, Pennsylvania, Oregon, and North Carolina have had incidents of property damage, personal injury, and fatalities resulting from rock slope failures. Just in 1992, Virginia had several property damage cases, at least one rock fall fatality case, and one personal injury case in the courts. As the Interstate Highway System continues to age, inventories of highway rock slopes and analyses of problem sites become vital. Of course, rock slope stability is not only of concern along highways, but also in open-pit mining, quarrying, and building construction.

SECTION II. BACKGROUND THEORY

A. OVERVIEW OF ROCK SLOPE ANALYSIS

The complete stability analysis of an existing (or proposed) rock slope involves five steps: understanding the geology, mapping the site, performing stereonet analyses, calculating safety factors, and, if needed, planning remediation. These steps are explained below and this exercise concentrates on the stereonet analyses.

1. Regional, local, and site geology

An understanding of rock slope stability at a site begins with an understanding of the geology, starting with the regional perspective and working down to the site. Sources of geologic information include library and office research (articles, reports, maps, air photos), discussions with colleagues, and field reconnaissance.

Before mapping discontinuities, a site reconnaissance must be conducted. This involves systematically walking the site (with maps and plans if available) to become familiar with all aspects of the project. Observations should be recorded in a field notebook or on an audio cassette recorder for later transcription. The general geologic nature of the site, rock types, types of discontinuities and their general characteristics, obvious clustering of discontinuity orientations, surface drainage, ground water characteristics, and major features such as faults should be noted.

2. Mapping the site

A rock slope stability analysis requires a survey of the orientations and characteristics of the discontinuities in the rock mass. Examples of discontinuities are joints, faults, shear zones, bedding surfaces, and foliations. The physical characteristics of discontinuities greatly affect slope stability and include geometry, spacing, surface roughness, physical properties of adjacent rock, presence of infilling material, and ground-water conditions. Discontinuities in a rock mass are sampled and mapped using procedures such as the following.

<u>Line mapping</u> - involves placing a 100 foot measuring tape along the slope face and recording data for every discontinuity that crosses the tape. Figure 1 is an example of a data sheet for line mapping. Included are measurements of position so that spacing may be statistically examined during computer analyses. The principal advantage of line mapping is the control that it imposes upon the collection of data for statistical purposes. A major disadvantage of line mapping is that it becomes tedious when large areas are mapped. It should be kept in mind that although much of the data are subjective in nature, they may be quite useful when analyzing potential failure surfaces.

<u>Window mapping</u> - all discontinuities falling within "windows" on the slope are examined. The author utilizes windows that are approximately 5' tall by 25' long with 10' to 25' between windows as permitted by site conditions. It is important collect a statistically significant number of discontinuities in the windows and to use sound geological judgement when visually examining areas outside the windows for anomalous features. Window mapping has the advantage of being slightly faster than line mapping but has less statistical control.

<u>Outcrop mapping</u> - limited discontinuity data may be obtained from rock outcroppings in the vicinity of proposed excavations. These data usually compare favorably with data collected after excavation except for having less detail and less resolution of the clusters.

<u>Oriented core logging</u> - cores are sometimes used to obtain discontinuity data in areas where excavation has not yet begun. Some means of orienting the core with respect to its insitu

position must be utilized. Some parameters, such as discontinuity length and continuity are impossible to obtain from oriented core.

Photographic mapping - photomosaics may be made and covered with clear plastic so that locations of discontinuities, changes in geologic nature, problem areas, and other significant features in

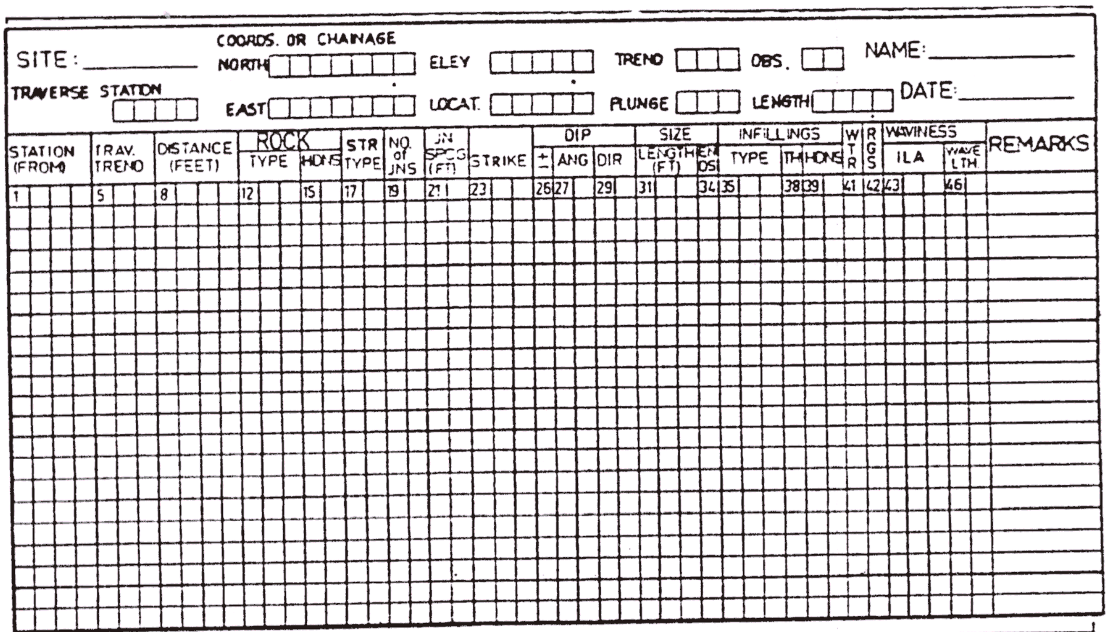


Figure 1. Typical data sheet for recording information during detail line mapping (from Piteau and Associates Limited, 1980).

a rock slope may be traced on the photos and annotated at the site. This should be done in addition to any of mapping techniques where possible. It allows a record of both the window and non-window areas to be made. Photographs also are of help in documenting any changes that occur in the slope with time.

3. Performing stereonet analyses

Stereonets permit the three-dimensional analysis of discontinuity orientations by stereographic projection. This enables the identification of unfavorable discontinuity orientations in a given slope or allows for the determination of more favorable slope geometries during the design phase. These are often referred to as **kinematic analyses**. Kinematics refers to the branch of dynamics that examines motion or potential motion without considering mass and force. Potential plane, wedge, and toppling rock failures may be identified kinematically on stereonets.

4. Calculating safety factors

Once discontinuities having unfavorable orientations are identified, safety factors against translational sliding may be determined by calculating the ratio of resisting forces to driving forces along discontinuities. Safety factors less than 1.0 indicate that driving forces are greater than resisting forces. A safety factor of 1.0 would theoretically indicate equilibrium. Safety factors of 1.2 to 1.3 are typically considered the minimum acceptable.

5. Remediation

Possible recommendations for remediation include: do nothing (for safe slopes or impossible slopes); provide drainage for excess water; redesign the rock slope to a more stable geometry; provide artificial support, netting, or catchment areas; or, relocate the project and/or affected people.

B. STEREONET BASICS

For analytical purposes, discontinuities are assumed to be planar. There are three possible representations of a plane in space on stereonets. They are poles, dip vectors, and great circles, as illustrated in Figure 2.

Geologists have traditionally used **poles** to represent planes. A pole is formed by passing a line perpendicular to the plane through the center of the reference sphere. The point where the line intersects the lower hemisphere is the pole and is projected upward to the stereonet (Figure 2.).

A **great circle** is formed by the intersection of the plane in space with the lower half of the reference sphere. The stereonet projection of this intersection is an arc called a cyclographic trace of the

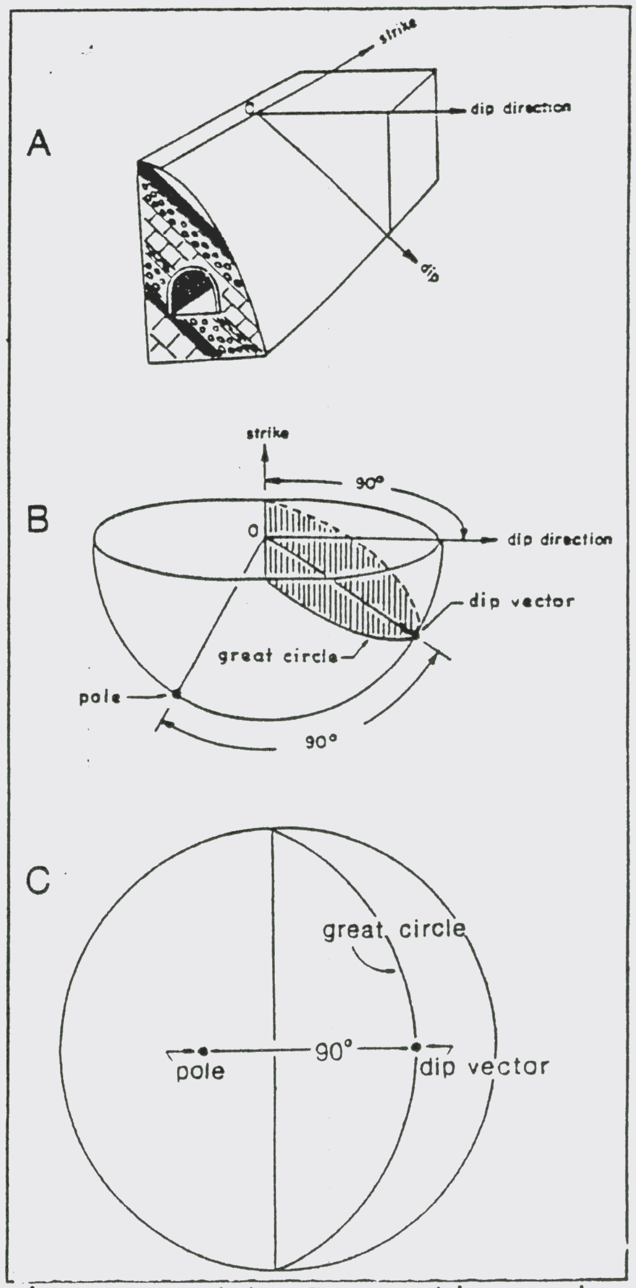


Figure 2. **(a)** Perspective view illustrating strike and dip of bedding surfaces. **(b)** Lower hemisphere illustration of poles, dip vectors, and great circles. **(c)** Stereonet projection of the representations from 2b (modified from Bassarab, 1979.)

plane, but commonly referred to as a great circle (Marchak and Mitra, 1988).

The **dip vector** is a single point, like the pole, except that it is plotted in the direction of the dip. Simply put, it is the midpoint of the great circle representation of the plane (Figure 2). As such, it clearly depicts the dip direction and dip value of the plane in space. The closer it is to the center, the steeper the dip. One advantage of the dip vector is that it enables one to rapidly visualize the orientations of planes in space with very little training.

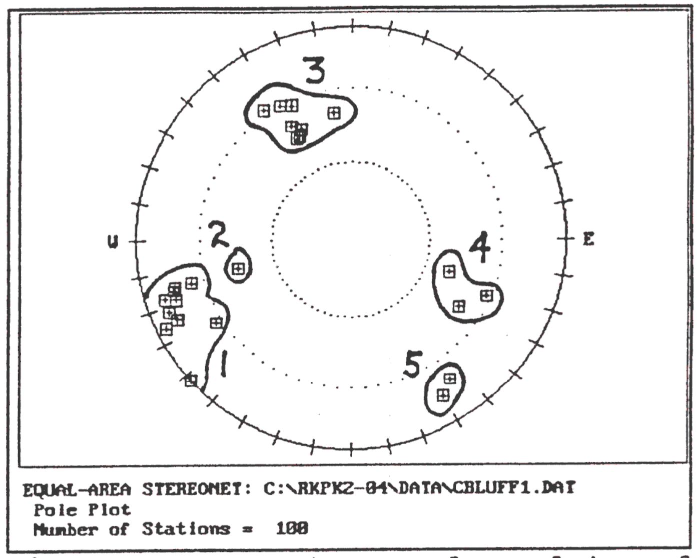


Figure 3. Computer **pole plot** of discontinuities from Cedar Bluff, Virginia.

Each of the representations has its own advantages and uses. Poles or dip vectors are used to represent individual discontinuities as single points, keeping the stereonet less cluttered than if great circles are used. On the other hand, great circles are used to represent slope faces so that they stand out clearly and the relationships between them and the individual discontinuities may easily be examined. Also, great circles are useful when representing clusters in wedge analyses as described later. Plotting procedures for all of the representations are described in Part F.

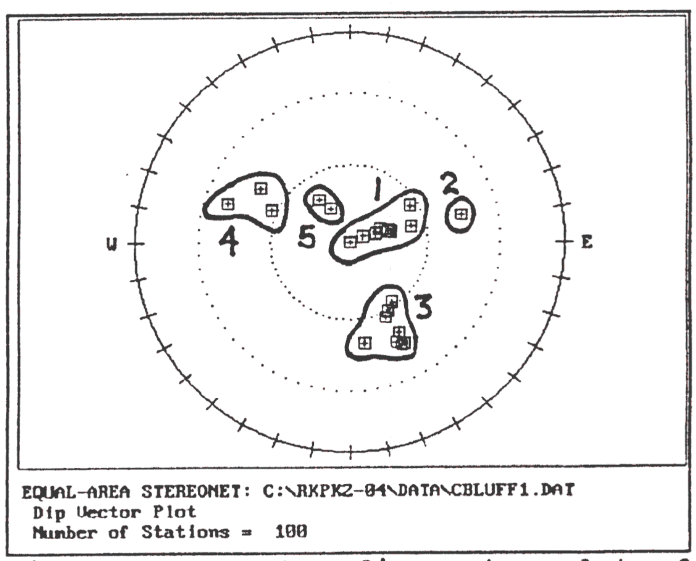


Figure 4. Computer **dip vector** plot of the same discontinuities from Cedar Bluff, Virginia.

C. DISCONTINUITY CLUSTER ANALYSIS

Unless a rock mass is severely fractured, several distinct clusters will be obvious when discontinuities are plotted as poles or dip vectors. The orientations of discontinuities in a rock mass are related to its geologic history. Traditionally, discontinuities have been plotted as poles in rock slope studies. However, dip vectors are rapidly gaining recognition as being easier to plot and interpret (Whisonant and Watts, 1989). Figure 3 is a pole plot of data from a site in the Appalachian Mountains of Virginia. The poles have been grouped into clusters by eye and numbered for identification. Figure 4 is a dip vector representation of the same data. Note the differences in appearance of the clusters between the two plots.

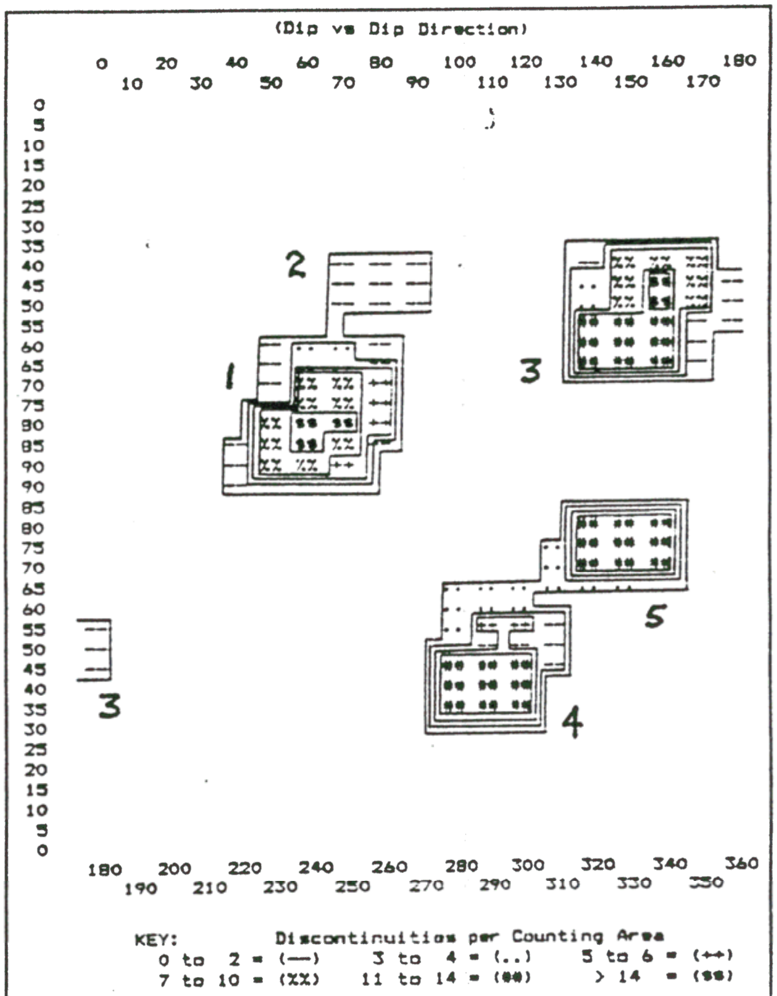


Figure 5. Computer contoured rectangular plot of data from Cedar Bluff, Virginia.

Discontinuity clusters are not always easy to identify by eye on a plot; hence, orientation data are sometimes contoured to make groupings more obvious. A number of techniques exist for contouring orientation data and the reader may wish to refer to Chapter 3 in Hoek and Bray (1981) for additional details. Most procedures involve the placement of a counting cell, or a net of counting cells, over the stereoplot and determining the number of discontinuities that fall within the counting cells at different positions on the plot. The resulting population density values then replace the plotted points on the stereonet. Portions of the plot having large numbers of discontinuities per unit area are therefore emphasized by large density values. Figure 5 illustrates data from Cedar Bluff, computer contoured in a rectangular plot format. The top half represents dip directions of 0° to 180° while the bottom half represents dip directions of 180° to 360°. Dip values are read along the side. Figure 6 is a projection of the contours from the rectangular plot to an equal-area pole plot.

The importance of discontinuity clustering can be seen in Figure 7. Spatial relationships between discontinuity clusters and the slope face determine what types of failures are possible. The greater the number of discontinuities a cluster contains, the greater the likelihood that a failure will involve members of that cluster, given the opportunity. A slope should thus be designed to minimize unfavorable orientations with respect to large or dense clusters. Slope investigators must keep in mind that the results of population contouring are heavily dependent on data collection procedures. Biases may be unknowingly introduced by the orientation of the slope and by collection methods. For example, discontinuities parallel or nearly parallel to the slope face are often under-represented in the data as they do not appear in the face as often as discontinuities perpendicular to the slope. Yet, those which parallel the face often control the stability.

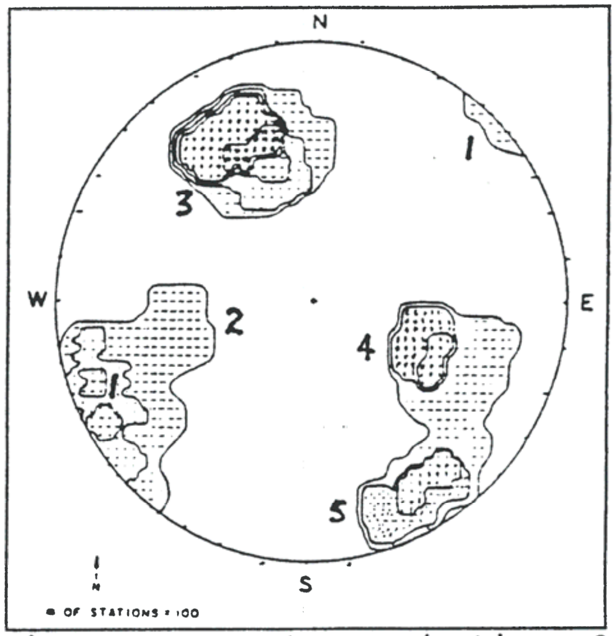


Figure 6. Computer projection of contoured data as poles.

D. DISCONTINUITY SIGNIFICANCE ANALYSIS

Watts' **D**iscontinuity **S**ignificance **I**ndex (DSI) is a rating of the importance of each discontinuity in a rock mass to the stability of any slope that could be cut into the rock. The concept is described in detail in Watts and West (1985) and Watts and West (1986). In some cases, one major discontinuity (like a fault) can be more important to the stability of a slope than a large, dense cluster of rough joints; yet, they all appear equal as "dots" on a standard plot. On plots where DSI values are indicated in some manner, a highly significant discontinuity will stand out clearly. It may or may not lie hidden within a cluster of other discontinuities. DSI values are extremely valuable for comparing discontinuities at a site. They are less useful when comparing between sites.

One simple type of DSI may be estimated on the site as data are collected. The slope investigator records a value based on his experience and on his understanding of the roles of various discontinuity characteristics. In this exercise, simple DSI values of 1, 2, or 3 will be assigned based on specific parameters in the data set. Although extremely useful, it is important to remember that DSI values are subjective.

More precise discontinuity significance indices can be calculated directly from the field data if appropriate parameters have been recorded. Parameters such as dip value, discontinuity length, infilling material, roughness, intact rock, and water conditions are among those that may be considered. The larger the DSI, the greater the possibility of failure along that discontinuity given an unfavorable geometry, as explained later. In other words, the DSI calculations combine several important characteristics to create a single value useful for comparing the importance of discontinuities to one another.

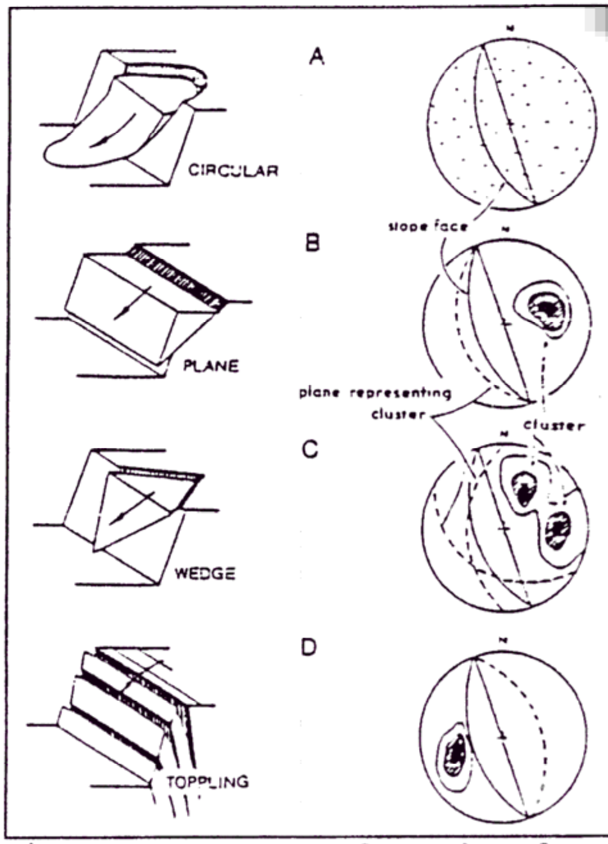


Figure 7. Types of rock slope failures and stereoplots of **pole** cluster orientations likely to produce them. (From Hoek and Bray, 1981.)

Figure 8 shows the general form of Watts' DSI equation. The complexity of the equation makes it impractical to calculate all of the DSI values for large data sets by hand. Computers handle it easily however. The derivation is treated in detail by Watts and West (1986). Although based on limiting equilibrium theory, discontinuity significance is not meant to replace safety factor calculations. The indices provide a means of quickly ranking discontinuities so that the more significant ones may receive greater attention. The significance values are intentionally independent of slope orientation, so that they may be of use before slope alignment is selected.

DSI values may be plotted on either rectangular dip plots or on stereonets. Data from Cedar Bluff, Virginia illustrate the DSI concept. Figure 9 is a plot of the maximum calculated DSI values occurring at each orientation on the plot. It is similar in appearance to a population plot which shows the number of discontinuities in the data set at each orientation. However, the numbers here represent the highest DSI values at each orientation.

In terms of population, Cluster 3 would be deemed most important as the field data show it to contain 35 discontinuities. Cluster 4 would be next in importance, containing 25, followed by Cluster 1, containing 16 discontinuities. However, failures involving the discontinuities of Cluster 4 would require the shearing of considerable intact rock, as the site investigation revealed those joints to be short and poorly connected. Hence, Cluster 4 is not as significant to the stability of the slope as its population might indicate.

$$DSI = \frac{10(W\sin\psi)^{1/N}}{[K_j(W\cos\psi - U)\,\mathrm{Tan}(\phi_j + JRC\log\sigma_j/\sigma) + K_m(C_m A + W\cos\psi\tan\phi_m)]^{1/N}}$$

Terms:

- N = function shape parameter
- W = weight of sliding block
- ψ = dip value of discontinuity
- K_j = decimal percentage of non-intact rock along discontinuity
- K_m = decimal percentage of intact rock along discontinuity
- U = uplift pressure due to water along length of discontinuity
- ϕ_j = friction angle along non-intact rock portions of discontinuity
- ϕ_m = friction angle of intact rock in the rock mass
- C_m = cohesion value for intact rock in the rock mass
- A = length of discontinuity including both intact and non-intact portions
- JRC = joint roughness coefficient value
- σ_j = unconfined compressive strength of rock adjacent to discontinuity
- σ = normal stress on discontinuity

Figure 8. General form of Watts' Discontinuity Significance Index Equation.

In terms of calculated DSI, Cluster 3 still is the most significant as it contains index values ranging from 8 to 11 (Figure 9). Cluster 1 is next in significance as it contains at least one discontinuity with an index value of 9, and the remaining clusters are all of nearly equal significance having index values of 3. Further investigation confirmed that Clusters 1 and 3 control the stability of this slope. Indeed, a failure involving those discontinuities was successfully predicted in 1983 (Watts and West, 1985).

E. KINEMATIC ANALYSES

Kinematic analyses are performed to determine which discontinuities have unfavorable orientations that could actually lead to sliding with respect to a specific slope geometry. The author has adopted the use of the term **critical** to refer to discontinuities that are both significant and kinematically possible.

1. Plane Failures

The basic concept of kinematic analysis for plane failure is straightforward. Two conditions must be met for sliding to occur. First, the discontinuity must dip more steeply than its friction angle. In simple terms, the friction angle is the minimum dip angle for which sliding will occur along a discontinuity. For example, if two saw-cut slabs of rock are placed together horizontally and slowly tilted, the top slab will begin to slide when the sliding surface reaches the friction angle. Of course, this description ignores some obvious factors such as cohesion and irregularities between the surfaces, hence it is conservative. It is useful nevertheless. Friction angle values can be obtained by performing

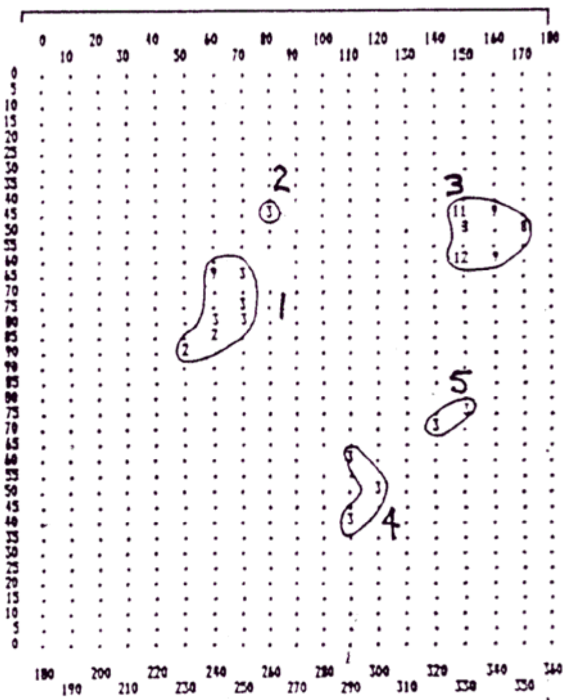


Figure 9. Maximum significance values for data from Cedar Bluff, Virginia.

direct shear tests on the discontinuities as described in the engineering literature. Friction angles for a typical competent rock are around 28° to 32°.

The second condition for sliding is that the discontinuity must **daylight** from the slope face in a down-dip direction. This means that the discontinuity must dip in the same general direction as the slope face, but less steeply. Sliding cannot occur if the discontinuity dips back into the slope because it is locked in place. Sliding can only rarely occur if the discontinuity dips in the same direction but more steeply than the slope face, as it too is locked in. An exception to the latter case would occur if another less steep weakness exists (or develops) thus providing a pathway to daylight.

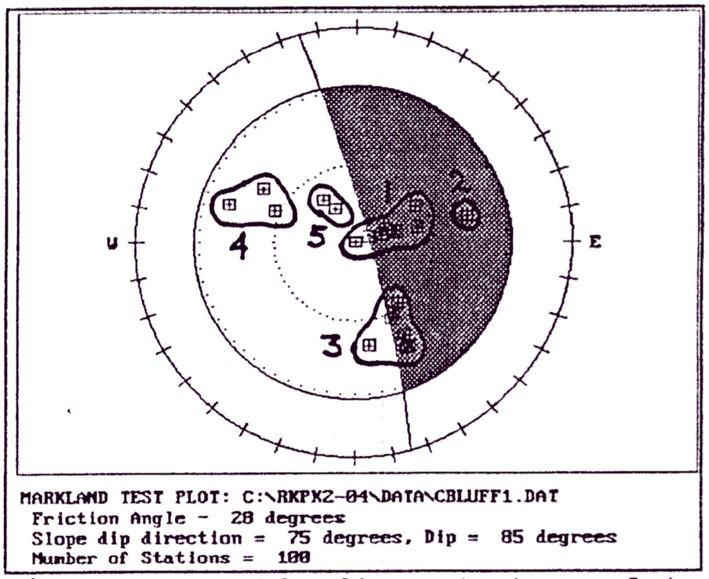


Figure 10. Markland's Test stereoplot. Dip vectors in shaded zone represent possible plane failures.

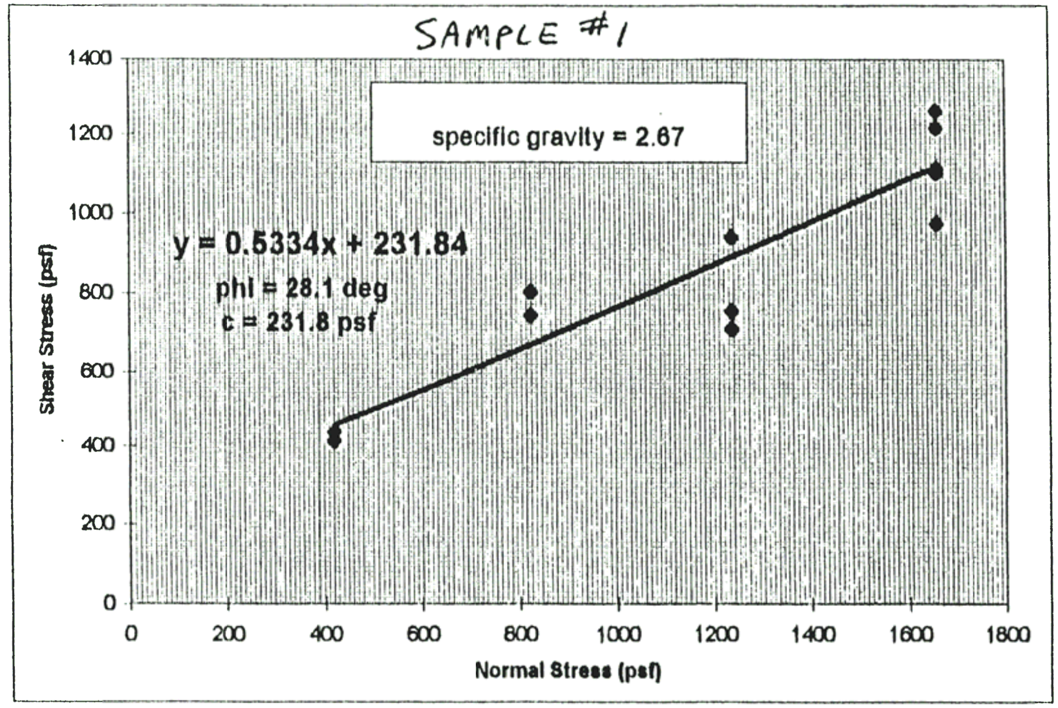
The two conditions necessary for sliding can be represented on a stereonet in the form of a crescent-shaped critical zone (Figure 10). Discontinuity dip vectors which lie within the critical zone dip more steeply than the friction angle of the rock because they are inside the friction circle. They dip less steeply than the slope face because they lie outside the great circle representing the slope face. Hence, Clusters 1, 2, and 3 in Figure 10 represent kinematically possible planar failures. This is referred to as **Markland's Test.**

Figure 11. Unstable bedding plane discontinuities dipping into a railroad cut near the Cedar Bluff site.

When the field data are examined carefully; however, the three kinematically possible failure surfaces are not all critical. For example, Cluster 2 contains only a few short and rough discontinuities, and has a very low DSI value. No failures involving this cluster were observed.

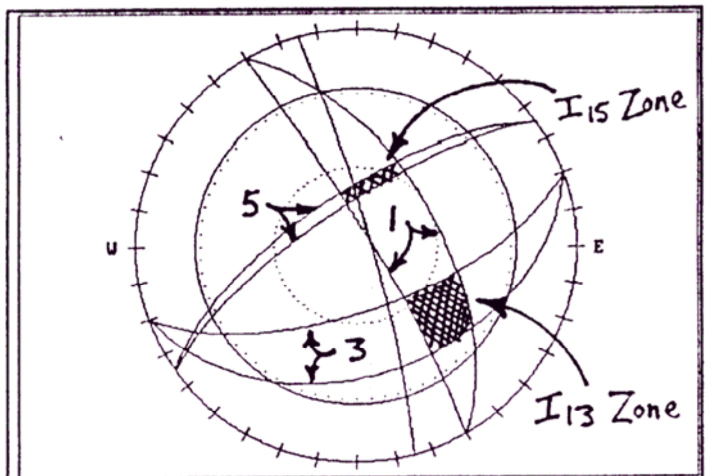
Direct Shear Pull Tests

normal stress (psf)	shear stress (psf)
419.459	435.580
419.459	412.655
824.246	802.384
824.246	745.071
1237.299	710.683
1237.299	756.534
1237.299	939.936
1237.299	939.936
1659.312	1111.875
1659.312	974.324
1659.312	1260.890
1659.312	1100.413
1659.312	1215.039



Selecting how the representative great circles should pass through the dip vector clusters (Figure 12) is a matter of debate, judgement and experience. The choice can profoundly affect the analysis. If the population of discontinuities is uniformly distributed within the cluster, the great circle should pass through the "center" of the cluster. If the density of dip vectors is greater in one part of the cluster, the representative great circle should be closer to that population center. Contouring can help make that call. On the other hand, if some discontinuities in the cluster have greater **significance**, the great circle should pass closer to them.

Another approach is to select great circles that "bound" the clusters. The result is a great circle "girdle" for each cluster, rather than a single great circle within each cluster. The intersections of the girdles are zones rather than points. If any portion of an intersection zone falls within the critical zone, then there are possible wedge failures among the discontinuities plotted. The results are more representative of possible wedge combinations in the data than is selecting one great circle per cluster.



MARKLAND WEDGE ANALYSIS: C:\RKPK2-84\DATA\CBLUFF1A.GRT
Friction Angle - 28 degrees
Slope dip direction = 75 degrees, Dip = 85 degrees

Figure 13. Modified test for wedge failure by bounding clusters 1, 3, and 5. Other clusters were omitted for clarity. Two intersection zones appear in critical zone.

The wedge analysis of Figure 12 indicates that Clusters 1 and 3 combine to form a critical wedge. Reexamination of the site revealed a wedge of that orientation in the rock mass, with tension cracks already forming along the crest. It failed as predicted in the spring of 1983. Sliding occurred along a Cluster 1 plane with a Cluster 3 plane acting as a release surface. Wedge intersections with other orientations are seen to fall within the critical zone, but a comparison of DSI values indicates that they do not involve high DSI discontinuities and thus are not critical.

F. PLOTTING PROCEDURES

1. Types of Stereonets

The reference sphere of Figure 2B may be projected to a two-dimensional stereonet in several ways. **Equal-area** (Schmidt) nets and **equal-angle** (Wulfe) nets are commonly used to analyze geological structures. Explanations of the projections can be found in most structural geology texts. The equal-area projection is used most often in slope stability studies because it preserves the area relationships useful in discontinuity contouring.

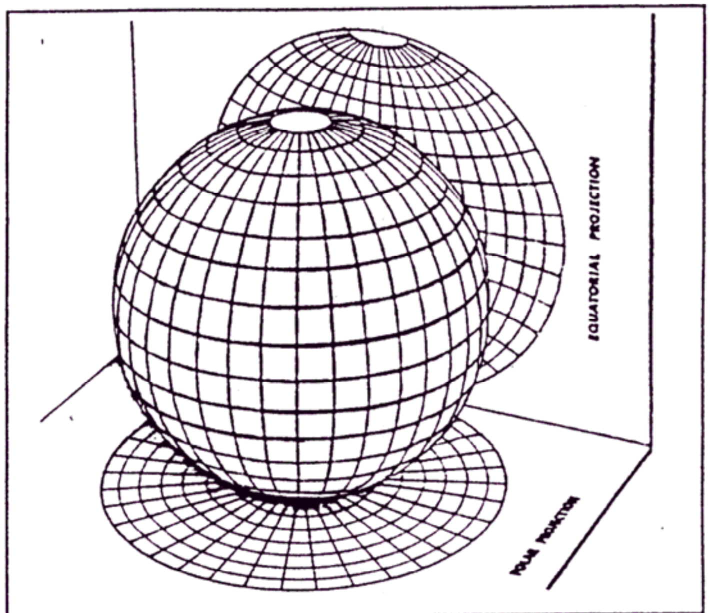


Figure 14. Equatorial and polar projections of stereonets. (From Hoek and Bray, 1981.)

Using the familiar earth longitude and latitude system for reference, the great circles are analogous to longitude and the small circles are analogous to latitude. These circles may be projected to stereonets in either an **"equatorial"** fashion or a **"polar"** fashion, as shown in Figure 14. Hence, on an equatorial stereonet, the great circles trend north-south while the small circles trend east-west. On the polar stereonet, the great circles appear as lines radiating outward from the center and the small circles are concentric about the center. These stereonets are simply two different views of the same reference sphere used as a three-dimensional angle measuring device. Choosing either of the stereonets is like "rotating" the device so that the more useful view is presented for the particular measurement to be made.

Great circles must be drawn using the equatorial stereonet. Poles, dip vectors, and friction circles may be plotted on either the equatorial stereonet or the polar stereonet. However, it is simpler to plot them on the polar stereonet as described below.

2. Plotting Geologic Structures on Stereonets

Dip vectors may be plotted by placing a piece of tracing paper on the polar stereonet. For reference, begin by tracing the outer circle (primitive) of the stereonet onto the tracing paper and marking the N, S, E, and W directions. Dip direction is read around the primitive clockwise from north, as on a compass. The dip value is measured inward from the primitive, which represents 0° dip, toward the center point, which represents a 90° dip for dip vectors (Figure 15a).

Poles may also be plotted on the polar stereonet. Begin as if plotting a dip vector; that is, reading the dip direction clockwise from north. The pole is then measured from the center point towards the outside of the stereonet in a direction opposite to the dip direction and in an amount equal to the plane's dip value.

When working with poles, the center represents 0° dip and the primitive represents 90° dip (Figure 15b).

Friction circles are plotted easily on the polar stereonet. The friction angle is measured inward from the primitive and a circle is drawn at that position about the stereonet center. Dip vectors falling inside dip more steeply than the friction angle (Figure 15c).

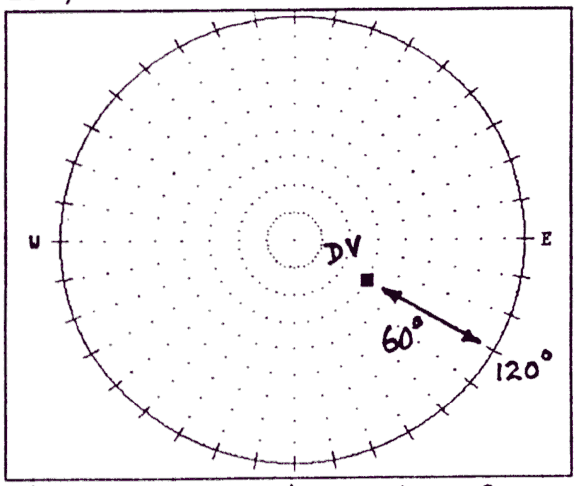


Figure 15a. Dip vector for a plane dipping 60° in a direction of 120° on a polar stereonet.

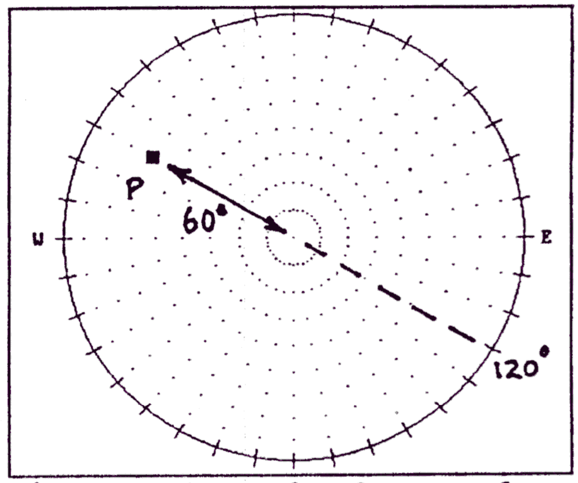


Figure 15b. Pole for a plane dipping 60° in a direction of 120° on a polar stereonet.

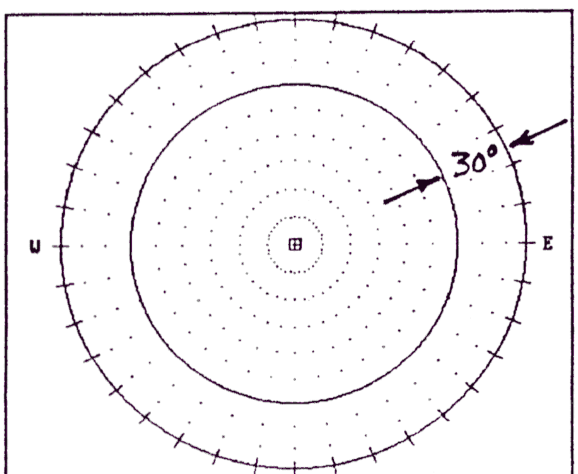


Figure 15c. Friction circle plotted at 30° on a polar stereonet.

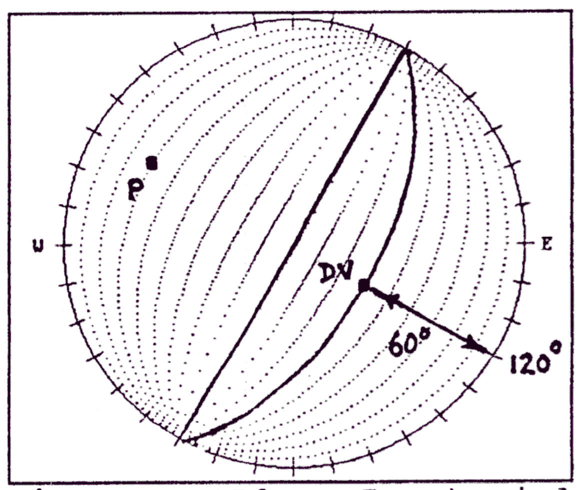


Figure 15d. Equatorial stereonet rotated beneath tracing paper to plot great circle for a plane dipping 60° in a direction of 120°.

Great circles are plotted by first placing the tracing paper on the equatorial stereonet with compass directions on the tracing paper aligned with compass directions on the stereonet. In this position, only great circles for planes dipping to the east or the west may be plotted. For other dip directions, the stereonet may then be rotated beneath the tracing paper until the correct orientation is obtained. In Figure 15d, the stereonet was rotated beneath the tracing paper until its E-W line was aligned with a dot placed at 120° on the tracing paper before rotation. Note that the same end result could be obtained by rotating the tracing paper such that the dot at 120° is brought to the E-W line on the stereonet. In either case, the dip angle is measured in from the primitive, the corresponding great circle is traced, and the tracing paper and stereonet are realigned.

SECTION III. PROBLEMS

In this exercise, you will analyze the stability of a highway roadcut based on the orientations and characteristics of geologic structures (discontinuities) in the rock mass. You will perform stereonet analyses to identify possible plane and wedge failures and examine the characteristics of each discontinuity in order to ascertain discontinuity significance indices. These operations are typical of the procedures that normally precede safety factor calculations.

PLANE FAILURE ANALYSES

1. Place a piece of tracing paper on the **polar stereonet.** Trace the primitive (outer circle) with a compass and label the N,S,E,W directions. Using the procedures outlined on the previous pages, plot dip vectors (use small dots) for all of the discontinuities in the sample detail line data.

2. Assume that the average friction angle (phi) for discontinuities in the rock mass is 32°. Draw the corresponding friction circle with a compass on the tracing paper. How many of the discontinuities in the data set dip more steeply than the friction angle?

3. Transfer the tracing paper to the **equatorial stereonet.** The rock slope face dips in a direction of N75°E and has a dip value of 85° (written as 075/85). Draw the slope face on the tracing paper as a great circle. How many discontinuities in the data set dip more steeply than the friction angle (as in question 2) **and** daylight down-dip out of the slope face? How many discontinuities in the critical zone have dip directions within 20° (plus or minus) of the slope face dip direction? Why is this of interest?

4. Examine the sample detail line data again, paying particular attention to the structure type, discontinuity length, roughness, and hardness of adjacent rock. Using only those parameters (ignore dip and dip direction), and your own perception of discontinuity significance based on those parameters, place a (1) after the last column of the sample data for each discontinuity that has low significance with regard to stability. Next, place a (3) after the last column for each discontinuity that seems highly significant to stability. Record a (2) for those discontinuities about which you are undecided (intermediate significance). How many did you indicate are insignificant? How many are highly significant? How many are of intermediate significance?

5. On the tracing paper, draw squares around the dip vector points deemed highly significant. Draw triangles around the dip vectors deemed intermediate. Leave the dip vectors deemed insignificant as dots. How many discontinuities of intermediate significance fall in the crescent-shaped critical zone? How many highly significant discontinuities fall in the crescent-shaped critical zone? After examining these results, which discontinuity orientations would you want to calculate planar safety factor calculations for (and examine more carefully in the field the next time you are at the site). In other words, which discontinuities are critical?

6. Describe the difference between significant discontinuities and critical discontinuities?

WEDGE FAILURE ANALYSES

7. To begin a wedge failure analysis, group the dip vectors on the tracing paper into clusters by eye and draw a curve around each cluster to enclose it. (Hint: points falling near the primitive may be in the same cluster as points 180° away that also are near the primitive.)

   Number each cluster on the tracing paper for identification purposes (numbering clockwise from north is an option that seems to work well).

8. With an **X**, mark a single position within each cluster that will serve to represent that cluster in the wedge analysis. Selecting the representative point is often a matter of debate, judgement and experience, as described in Section II. And, it can profoundly effect the analysis.

   If the population of dip vectors is uniformly distributed within the cluster, set the point in the "center" of the cluster. If the density of dip vectors is greater in one part of the cluster, shift the representative point closer to the population center. If some discontinuities in the cluster have higher discontinuity significance than others, shift the point closer to them. Wherever you set the representative point, remember that for cursory purposes, we are representing an entire cluster with only a single point. It is a very useful tool, but it is only an approximation.

Write the cluster numbers and their corresponding dip directions and dip values below using the *###/##* format. (Hint: This is easiest if you place the tracing paper on the **polar stereonet.**)

9. With the tracing paper on the **equatorial stereonet**, rotate the "X" representative point for each cluster to the equator and trace the corresponding great circle for each cluster (use dotted lines). How many wedge intersections fall within the crescent-shaped critical zone?

On the tracing paper, label each intersection with an **I** followed by the cluster numbers involved. For example, $\mathbf{I}_{45}$ would indicate an intersection of planes from Cluster 4 and Cluster 5. For each wedge intersection, write the corresponding trend and plunge (direction of plunge and dip of plunge) of the line of intersection below in the form of *###/##*. (Hint: This is easiest if you place the tracing paper back on the **polar stereonet.**)

Why is the 20° (plus or minus) zone with respect to the slope face dip direction less relevant for wedge failures than for plane failures?

10. The final step is to identify the critical wedge intersections. Using your estimations of discontinuity significance (as shown by dots, triangles, and squares on your tracing paper), rank the wedge intersections within the critical zone with regard to potential instability. For example, an intersection of clusters containing highly significant discontinuities has higher potential for failure than an intersection of clusters containing insignificant discontinuities. Write your ranking below (from highest to lowest).

SECTION IV. SELECTED REFERENCES

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SECTION V. ABOUT THE AUTHOR

DR. CHESTER F. WATTS (SKIP)

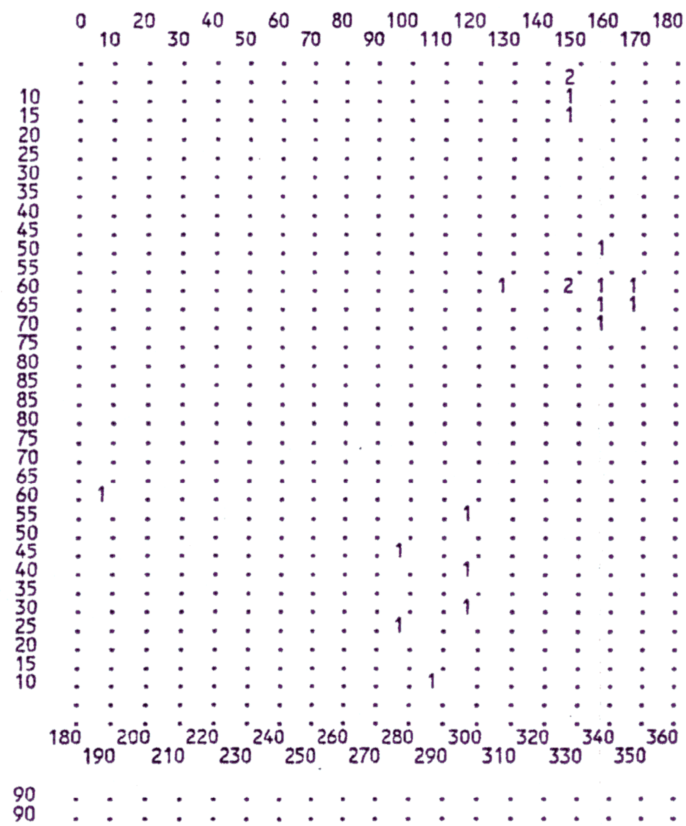
Dr. Watts received his B.S. in geology from Virginia Tech in 1974 and his PhD in engineering geology from Purdue University in 1983. He is the author of the internationally-used ROCKPACK microcomputer programs for analyzing rock slope stability. As a consultant, Dr. Watts has worked with numerous state highway departments, federal agencies, and private consulting firms. He serves as an expert in slope stability and mass wasting for the Virginia Office of the Attorney General. He also serves on the state geologic mapping advisory committee to the National Geologic Mapping Program. Dr. Watts is currently the Director of the Institute for Engineering Geosciences and Professor of Geology at Radford University, Radford, Virginia.

FIELD DATA FOR PROBLEM - PAGE 1

JNT#	TRAV	DIST	RKTP	HDS	STR	#JNS	JNSP	DIPDR	DIP	JNTLN	CONT	FLT	FLTH	FLHDS	WTR	RGHNS	WAVILA	WAVLN
1001	345	00.5	2	10	04	00	00	304	28	025.0	0	000	0	00	0	2	00.0	000.0
1002	345	01.0	2	10	04	00	00	290	12	025.0	0	000	0	00	0	2	00.0	000.0
1003	345	00.0	2	10	04	00	00	298	40	025.0	0	000	0	00	0	2	00.0	000.0
1004	345	00.0	2	10	04	00	00	296	56	025.0	0	000	0	00	0	2	00.0	000.0
1005	345	00.0	2	10	04	00	00	282	46	025.0	0	000	0	00	0	2	00.0	000.0
1006	345	00.0	2	10	04	00	00	282	24	025.0	0	000	0	00	0	2	00.0	000.0
1007	345	00.0	2	07	01	00	00	135	58	100.0	0	000	0	00	0	1	00.0	000.0
1008	345	00.0	2	07	01	00	00	148	62	100.0	0	000	0	00	0	1	00.0	000.0
1009	345	00.0	2	07	01	00	00	150	58	100.0	0	000	0	00	0	1	00.0	000.0
1010	345	00.0	2	07	01	00	00	158	58	100.0	0	000	0	00	0	1	00.0	000.0
1011	345	00.0	2	07	01	00	00	160	64	100.0	0	000	0	00	0	2	00.0	000.0
1012	345	00.0	2	07	01	00	00	160	68	100.0	0	000	0	00	0	2	00.0	000.0
1013	345	00.0	2	07	01	00	00	162	52	100.0	0	000	0	00	0	2	00.0	000.0
1014	345	00.0	2	07	01	00	00	170	58	100.0	0	000	0	00	0	1	00.0	000.0
1015	345	00.0	2	07	01	00	00	174	64	100.0	0	000	0	00	0	1	00.0	000.0
1016	345	00.0	2	07	01	00	00	188	58	100.0	0	000	0	00	0	1	00.0	000.0
1017	345	00.0	2	10	04	00	00	146	04	002.0	0	000	0	00	0	2	00.0	000.0
1018	345	00.0	2	10	04	00	00	150	08	002.0	0	000	0	00	0	2	00.0	000.0
1019	345	00.0	2	10	04	00	00	152	14	002.0	0	000	0	00	0	2	00.0	000.0
1020	345	00.0	2	10	04	00	00	152	04	002.0	0	000	0	00	0	2	00.0	000.0

JNT# TRAV DIST RKTP HDS STR #JNS JNSP DIPDR DIP JNTLN CONT FLT FLTH FLHDS WTR RGHNS WAVILA WAVLN

RECTANGULAR DIP PLOT



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DATA FOR DSI ANALYSIS

1. HDS = Hardness; 1 = very soft, 10 = average, 13 = very hard
2. STR = Structure type; 1 = bedding, 2 = joints, 3 = faults, 4 = foliati
3. JNTLN = Joint length, in feet
4. RGHNS = Roughness; 1 = very smooth, 5 = very rough

JNT#	TRAV	DIST	RKTP	HDS	STR	#JNS	JNSP	DIPDR	DIP	JNTLN	CONT	FLT	FLTH	FLHDS	WTR	RGHNS	WAVILA	WAVLN
1021	345	00.0	2	10	04	00	.00	154	08	002.0	0	000	0	00	0	2	00.0	000.0
1022	345	00.0	2	10	04	00	00	158	02	002.0	0	000	0	00	0	2	00.0	000.0
1023	345	00.0	2	10	04	00	00	330	02	002.0	0	000	0	00	0	2	00.0	000.0
1024	345	00.0	2	10	04	00	00	334	04	002.0	0	000	0	00	0	2	00.0	000.0
1025	345	00.0	2	10	04	00	00	006	62	004.0	0	000	0	00	0	3	00.0	000.0
1026	345	00.0	2	10	04	00	00	028	54	004.0	0	000	0	00	0	3	00.0	000.0
1027	345	00.0	2	10	04	00	00	028	58	004.0	0	000	0	00	0	3	00.0	000.0
1028	345	00.0	2	10	04	00	00	028	62	004.0	0	000	0	00	0	3	00.0	000.0
1029	345	00.0	2	10	04	00	00	030	64	004.0	0	000	0	00	0	3	00.0	000.0
1030	345	00.0	2	10	04	00	00	034	58	004.0	0	000	0	00	0	3	00.0	000.0
1031	345	00.0	2	10	04	00	00	046	56	004.0	0	000	0	00	0	3	00.0	000.0
1032	345	00.0	2	07	03	00	00	036	62	100.0	0	000	0	00	0	1	00.0	000.0
1033	345	00.0	2	10	04	00	00	068	46	025.0	0	000	0	00	0	2	00.0	000.0
1034	345	00.0	2	10	04	00	00	070	62	025.0	0	000	0	00	0	2	00.0	000.0
1035	345	00.0	2	10	04	00	00	074	56	025.0	0	000	0	00	0	2	00.0	000.0
1036	345	00.0	2	10	04	00	00	080	54	025.0	0	000	0	00	0	2	00.0	000.0
1037	345	00.0	2	10	04	00	00	080	64	025.0	0	000	0	00	0	2	00.0	000.0
1038	345	00.0	2	10	04	00	00	088	54	025.0	0	000	0	00	0	2	00.0	000.0
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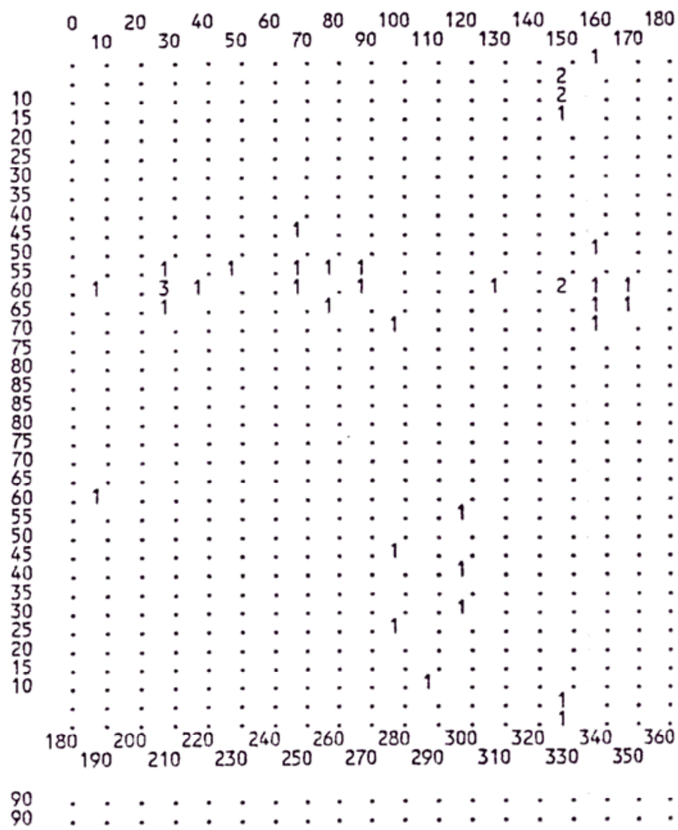
1040	345	00.0	2	10	04	00	00	104	68	025.0	0	000	0	00	0	2	00.0	000.0

JNT# TRAV DIST RKTP HDS STR #JNS JNSP DIPDR DIP JNTLN CONT FLT FLTH FLHDS WTR RGHNS WAVILA WAVLN

RECTANGULAR DIP PLOT



FILE(S) = / B:\PROBLEM.DAT

DATA FOR DSI ANALYSIS

1. HDS = Hardness; 1 = very soft, 10 = average, 13 = very hard
2. STR = Structure type; 1 = bedding, 2 = joints, 3 = faults, 4 = foliati
3. JNTLN = Joint length, in feet
4. RGHNS = Roughness; 1 = very smooth, 5 = very rough

Roderic Brame 11/01/93
Engineering Geology
Stereonet Analysis for Rock Slope Stability

2. **29** discontinuities from the data provided dip more steeply than the friction angle.
3. **19** discontinuities deep more steeply than the friction angle and less steeply than the slope of the rock cut. **7** of the discontinuities also fall within the critical zone that is defined by Dr. Skip Watts. The stereonet analysis of the data that shows points within the critical zone and within 20 degrees of the dip direction of the slope shows that the geometry of the slope and discontinuities show that it is possible for a planer failures to occur.
4. **15** discontinuities were marked as insignificant because of their length, structure type, and roughness. **17** were marked intermediate with joint lengths of at least 25 feet, structure being that of a foliation, and a roughness no greater than 3. **8** were marked as being highly significant due to long joint length, fault or bedding structure, and roughness being a 1.
5. **8** intermediate discontinuities fall within the critical zone. **4** highly significant discontinuities fall within the critical zone however none fall within 20 degrees of the dip direction of the slope. I would consider all of the possibilities within the critical zone with special consideration and safety factor calculations for the # 2 group of discontinuities and the Fault that lies within the group #1 discontinuities.
6. Significant discontinuities are those that contain properties that would indicate a weaker joint that would be more easily disturbed because of joint length, smoothness, or type of structure. Critical discontinuities are those that are significant discontinuities that fall within the critical zone and especially those that fall within 20 degrees of the dip direction of the slope.

Wedge Failure Analysis

8. 1 = 032, 60
2 = 081, 59
3 = 152, 62
4 = 152, 02
5 = 291, 34

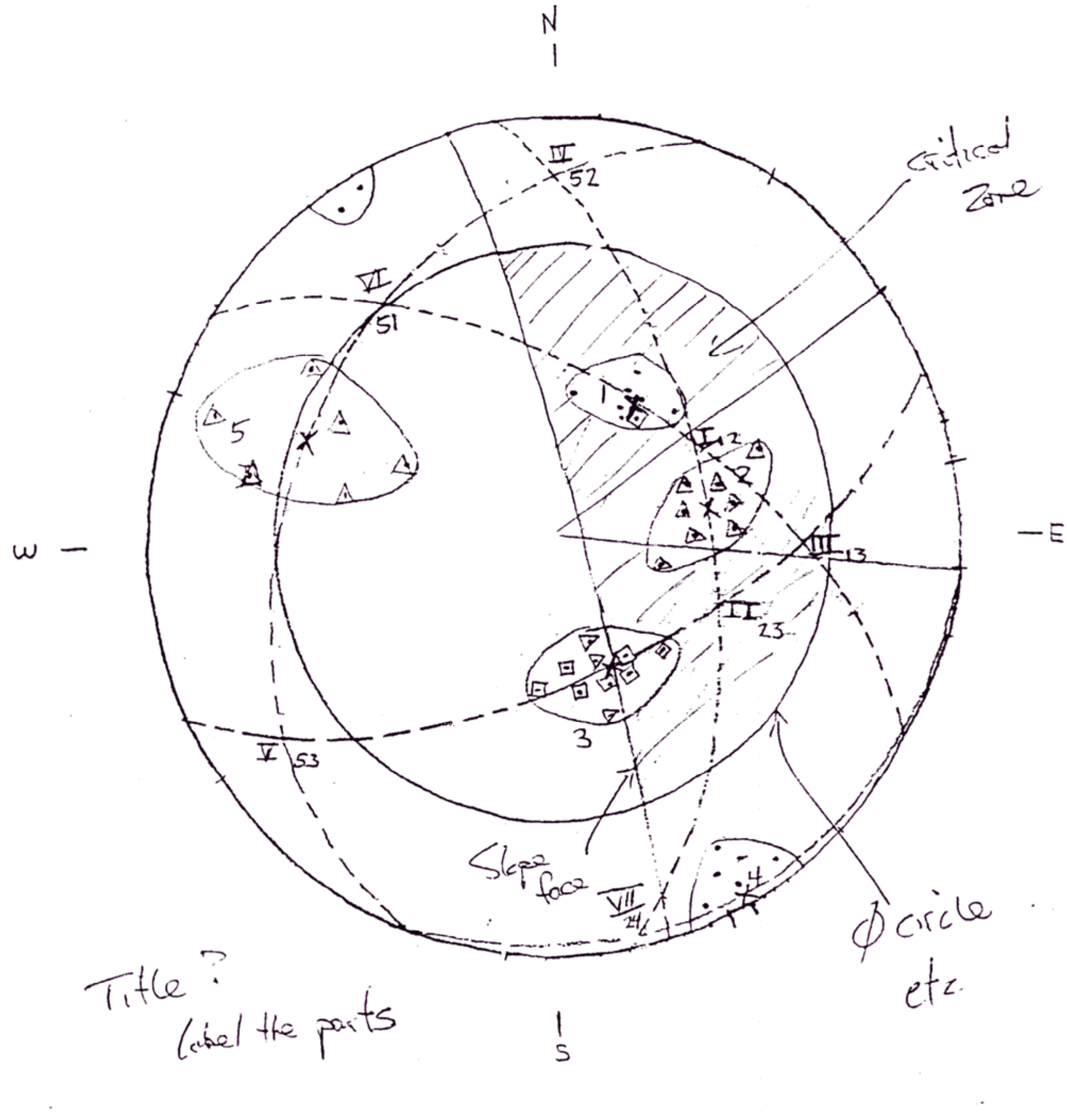
9. There are **3** wedge intersections that fall within the critical zone.

I	1:2	058, 56	IN THE CRITICAL ZONE	WITHIN 20 DEGREES
II	2:3	113, 54	IN THE CRITICAL ZONE	WITHIN 20 DEGREES
III	1:3	092, 38	IN THE CRITICAL ZONE	
IV	2:5	001, 16		
V	3:5	236, 20		
VI	1:5	324, 31		
VII	2:4	163, 11		

The plus or minus 20 degrees zone has less relevance with wedge failures because wedge failures create sections of rock that are not "locked" into the slope. Wedge failure geometry indicates essentially disconnected blocks of rock, if discontinuities are continuous and smooth, which movements are more dependent on the values of the resisting forces and driving forces. Wedge failures would have greater driving force if within the 20 degree zone but where a plane failure outside the zone would not occur because the rocks in the slope would prevent it a wedge failure would have no such prevention.

10. I 1:2 Highest
III 1:3
II 2:3 Lowest

RODERIC BRAME



Title? label the parts

A P P E N D I X   B

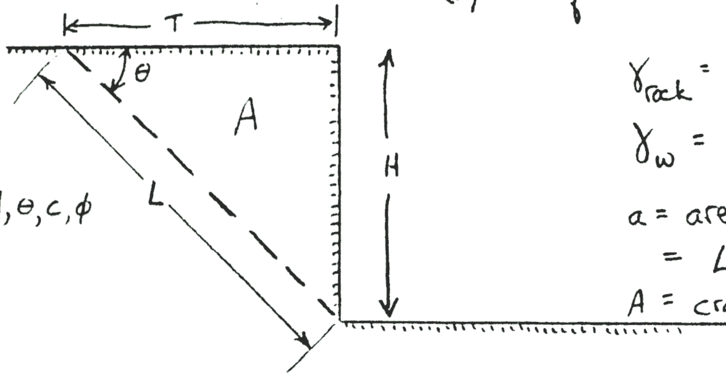
EXERCISE TWO

An Introduction to Plane Failure Safety Factor Calculations Including Artificial Support

The ROCKPACK II User's Manual is written under the assumption that users are already knowledgeable and competent in standard rock slope stability analysis methods. This Appendix is included simply as a refresher. For more detailed information on rock slope stability theory, please refer to the references listed.

Rock Slope Stability Calculations – Vertical Slope

(by limit equilibrium theory)



Given: H, θ, c, ϕ

γ_{rock} = unit weight of rock

γ_w = 62.4 pcf

a = area of sliding surface for a "unit slope"
= L × 1′

A = cross-sectional area of sliding mass

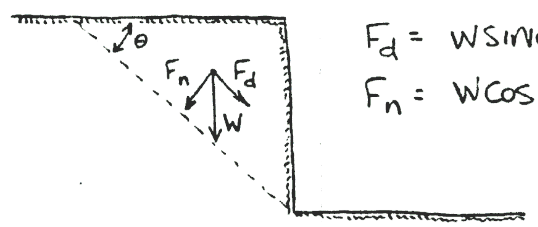
Steps

(1.) Find T, L, A: $T = \frac{H}{\tan\theta}$; $L = \frac{H}{\sin\theta}$; $A = \frac{HT}{2} = \frac{H^2}{2\tan\theta}$

(2.) Find Volume of Sliding mass: $V = A \times 1'$ (unit slope) units = ft^3

(3.) Find Weight: $W = V \times \gamma_{rock}$ units = lbs

(4.) Find driving force (F_d) and normal force (F_n):



$F_d = W\sin\theta$

$F_n = W\cos\theta$

(5.) Find resisting force (F_r):

$$F_r = ca + F_n\tan\phi = ca + (W\cos\theta)\tan\phi$$

(6) Find safety factor (FS):

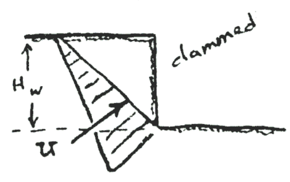
$$FS = \frac{F_r}{F_d} = \frac{ca + (W\cos\theta)\tan\phi}{W\sin\theta}$$

Theoretically unsafe if FS ≤ 1.0
FS = 1.3 generally used for design
If c = 0, $FS = \frac{\tan\phi}{\tan\theta}$

(7) If surface saturated find uplift pressure (u):

Free draining: $u = \frac{1}{4} a \gamma_w H_w$

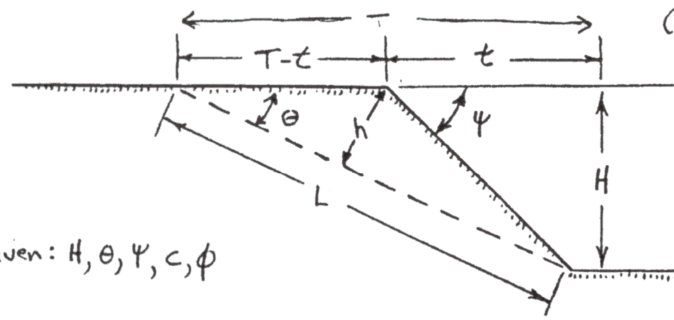
Ice dammed: $u = \frac{1}{2} a \gamma_w H_w$



(8) Find $FS_{saturated}$:

$$FS_{sat} = \frac{ca + (W\cos\theta - u)\tan\phi}{W\sin\theta}$$

ROCK SLOPE STABILITY CALCULATIONS - INCLINED SLOPE
(by limit equilibrium theory)



γ_{rock} = unit weight of rock

γ_w = 62.4 pcf

$a = L \times 1'$ (unit slope)

A = cross-sectional area of sliding mass

Given: H, θ, ψ, c, ϕ

STEPS

1. Find T, t, L, h, A: $T = \frac{H}{\tan\theta}$; $t = \frac{H}{\tan\psi}$; $h = \sin\theta(T-t)$; $L = \frac{H}{\sin\theta}$;

$$A = \frac{1}{2}hL = \frac{\sin\theta(T-t)H}{2\sin\theta} = \frac{(T-t)H}{2} = \frac{\frac{H^2}{\tan\theta} - \frac{H^2}{\tan\psi}}{2} = \frac{H^2}{2\tan\theta} - \frac{H^2}{2\tan\psi}$$

2. Find volume of sliding mass: $V = A \times 1\text{ ft}$ (unit slope) (ft^3)

3. Find weight: $W = V \times \gamma_{rock}$ (lbs)

4. Find driving force (F_d): $F_d = W\sin\theta$
   and normal force (F_n): $F_n = W\cos\theta$

5. Find resisting force (F_r): $F_r = ca + F_n\tan\phi = ca + (W\cos\theta)\tan\phi$

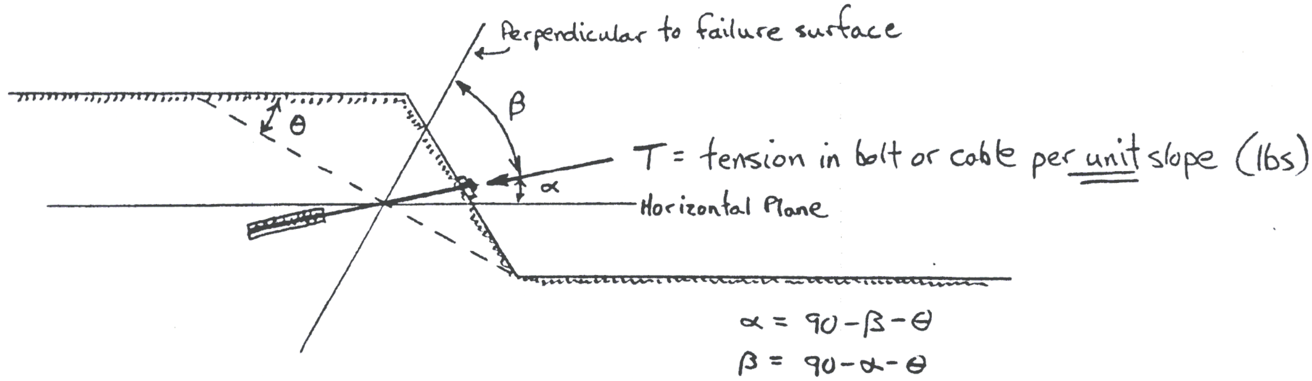
6. Find safety factor (FS): $FS = \frac{F_r}{F_d} = \frac{ca + (W\cos\theta)\tan\phi}{W\sin\theta}$

7. If surface is saturated find uplift pressure (U):
   Free draining: $U = \frac{1}{4} a \gamma_w H_w$ (see page 1)
   Ice dammed: $U = \frac{1}{2} a \gamma_w H_w$

8. Find $FS_{saturated}$:

$$FS_{sat} = \frac{ca + (W\cos\theta - U)\tan\phi}{W\sin\theta}$$

ROCK SLOPE STABILITY - ARTIFICIAL SUPPORT
(Rock bolts or cables)



Components of Tension (T) with respect to failure plane

Resisting: $T_r = T \sin\beta$

Normal: $T_n = T \cos\beta$

$$FS = \frac{ca + (W\cos\theta - u + \underbrace{T\cos\beta}_{T_n})\tan\phi}{W\sin\theta - \underbrace{T\sin\beta}_{T_r}}$$

GEOL 455 - ROCK SLOPE STABILITY ANALYSIS PROBLEMS

Given: A slope with a height of 100' and inclination (ψ) of 85°, Potential failure plane dips out of rock face at 45° (θ), γ_{rock} = 165 pcf, ϕ = 28°, c = 300 psf.

1. Calculate the safety factor of the slope dry.
2. Calculate the safety factor of the slope saturated, free draining.
3. Calculate the safety factor saturated, ice-dammed.

Given: Cable bolts are installed which provide a force (T) of 55 kips (55,000 lbs) per unit width of slope, at an angle β = 30°

4. Calculate the new safety factor for the dry slope.
5. Calculate the new safety factor for saturated free draining case.
6. Calculate the new safety factor for saturated ice-dammed case
7. Would you park your car under this slope?

BRIEF EXPLANATION OF DIP VECTOR STEREONET INTERPRETATION

Dip vector stereonet projection is a tool that may be used to represent the orientations of discontinuities in a rockmass with respect to existing or proposed rock slopes for the purpose of identifying potential plane, wedge, and toppling failures.

Potential Plane Failures:

The stereonet in Figure 1 contains discontinuities plotted as small squares. The dip value of each is indicated by radial position. That is, points on the outer circle have a zero dip (horizontal surfaces), 30° dip is represented by the first dotted circle, 60° dip is represented by the inner dotted circle, and 90° dip (vertical surfaces) is represented by the stereonet center. Dip direction is indicated by the compass direction of points referenced to the stereonet center. Points falling within the shaded moon-shaped area are steeper than the friction angle yet less steep than the slope face hence they daylight and are potential failure surfaces. Safety factors should be calculated for those points. (Note: points dipping most directly out of the slope face, as in the "critical zone central region" of Figure 3 below, are the most likely plane failures.)

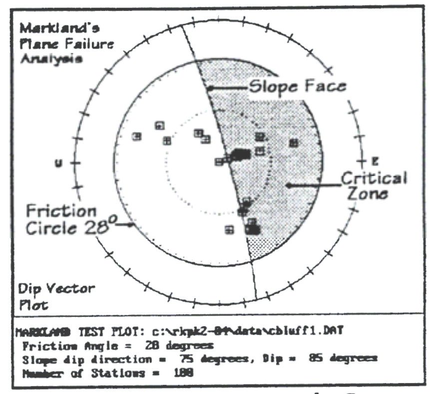


Figure 1. Potential plane failures.

Potential Wedge Failures:

Great circles may be drawn through clusters of points or individual points to represent those dipping planes. If any intersections between these great circles fall within the moon-shaped shaded area, as in Figure 2, wedge failures from the rock mass are possible. Wedge failure safety factors should be calculated.

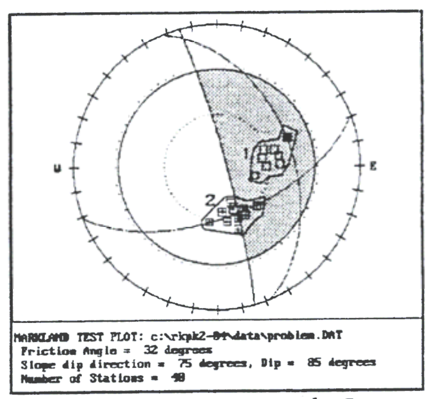


Figure 2. Potential wedge failure.

Potential Toppling Failures:

Discontinuities dipping back into a rock mass may cause rock blocks to topple out of the rock mass. The pie-shaped shaded area on the west side of Figure 3 outlines the areas of orientations that could lead to toppling failures. Overturning safety factors should be calculated for discontinuities falling within that area.

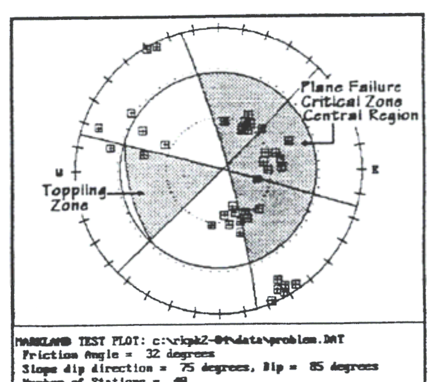


Figure 3. Potential toppling failures.

For more detailed explanation see ROCKPACK II User's Manual

ROCKPACK II - Field Reference Sheets for Data Collection

Hardness Input Code	Consistency	Field Identification	Approximate Range of Unconfined compressive strength Kg/cm^2 (Approx. Tons/ft^2)	psi
1	very soft	Easily penetrated several inches by fist	< 0.25	< 3.5
2	soft	Easily penetrated several inches by thumb	0.25-0.5	3.5-7
3	firm	Can be penetrated several inches by thumb with moderate effort	0.5-1.0	7-14
4	stiff	Readily indented by thumb but penetrated only with great effort	1.0-2.0	14-28
5	very stiff	Readily indented by thumbnail	2.0-4.0	28-56
6	hard	Indented with difficulty by thumbnail	>4.0	> 56
7	extremely soft rock	Indented by thumbnail	2.0-7.0	28-100
8	very soft rock	Crumbles under firm blows with point of geological pick, can be peeled by a pocket knife	7.0-70	100-1000
9	soft rock	Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow of geological pick.	70-280	1000-4000
10	average rock	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single firm blow of hammer end of geological pick	280-560	4000-8000
11	hard rock	Specimen required more than one blow with hammer end of geological pick to fracture it	560-1120	8000-16,000
12	very hard rock	Specimen required many blows of hammer end of geological pick to fracture it	1120-2240	16,000-32,000
13	extremely hard rock	Specimen can only be chipped with geologic pick	> 2240	> 32,000

4.3 HARDNESS

Category	Degree of Water
1	The discontinuity is tight; water flow along it does not appear possible.
2	The discontinuity is dry with no evidence of water flow.
3	The discontinuity is dry with evidence of water flow, rust staining of discontinuity surface, etc.
4	The discontinuity is damp but no free water is present.
5	The discontinuity shows seepage, occasional drops of water, no continuous flow.
6	The discontinuity shows a continuous flow of water.

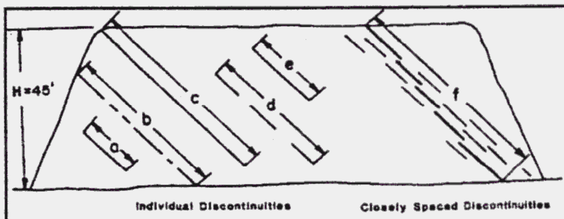
4.6 WATER

Input Value	Remark
0	Discontinuity Filled
1	JRC ≃ 5
2	JRC ≃ 10
3	JRC ≃ 15
4	JRC ≃ 20

4.8 b JRC INPUT CODES

DESCRIPTION	INPUT CODE
Zero % intact rock along discontinuity	1
Zero to 5% intact rock along discontinuity	2
Greater than 5% intact rock along discontinuity	3

4.4a CONTINUITY



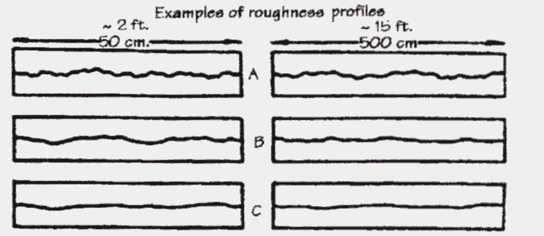
Discontinuity	Length	Ends Visible	Continuity Input Code	Length Input Code
a	16'	both	1	16.2
b	45'	neither	2	45.0
c	60'	one	1	60.1
d	32'	both	3	32.2
e	21'	both	1	21.2
f	51'	neither	2	51.0

4.4b LENGTH

0	Air (A) - total void exists between the walls of the plane.
1,2	Soil - Clay (C), sand (S)
3	Calcite (Z)
4	Detritus (D) - debris washed into an open fracture.
5	Evaporites (E) - gypsum, halite, anhydrite
6	Feldspar (F) - hard, often pink, insoluble, good cleavages, easily weathered
7	Gouge (G) - wall rock is often ground up by movements along a fault zone. Gouge is the result of the accelerated weathering of the resulting fine grained materials; it is generally a green clay.
8	Breccia (B) - consolidated angular rock fragments larger than sand grains resulting from fault movement.
9	Ore (Ø) - valuable
10	Quartz (Q) - hard, white and insoluble

4.5 INFILLING TYPES

Examples of roughness profiles



A. Rough undulating - tension joints, rough sheeting, rough bedding. JRC = 20

B. Smooth undulating - smooth sheeting, non - planar foliation, undulating bedding. JRC = 10

C. Smooth nearly planar - planar shear joints, planar foliation, planar bedding. JRC = 5

Barton's definition of Joint Roughness Coefficient JRC.

4.8a JRC EXAMPLES

Determination of Shear Strength Along Rock Discontinuities by Pull Testing

Key Terms

discontinuities, friction, cohesion, normal stress, shear stress, angle of repose

Introduction

The stability and safety of a rock slope is controlled primarily by the ***orientations*** and ***physical characteristics*** of ***discontinuities*** within the rock itself. Discontinuities are structural weaknesses formed within a rock mass as a result of various geologic processes acting on the rock over time. Types of discontinuities include faults, bedding planes, joints, and foliations.

The effect of discontinuity orientations is determined using three-dimensional stereonet techniques. The physical characteristics of discontinuity surfaces determine the amount of ***shear strength*** available to resist sliding.

A common dilemma in rock slope stability analysis and design is selecting the ***shear strength*** values known as ***friction*** and ***cohesion*** for the discontinuities in the rock mass. Workers often chose strength parameters from reference books in hopes that their rocks' properties will be similar, or rely on values used in previous studies, or simply use the time-honored rule-of-thumb that "friction angle is probably around 32^{o}". However, using values that are too high is risky from the safety standpoint and using values that are too low may result in over-design and be costly.

Brief Discussion of Simple Discontinuity Shear Strength

It is a well-known fact that ***shear strength*** (shear stress required to cause sliding to begin) increases when normal stress (stress pressing the surfaces together) also increases. It is for this reason that we add weight over the drive wheels of cars during the winter to increase traction on ice.

Laboratory tests are conducted for rock surfaces by measuring how much force it takes to make one rock block slide across another rock block as the blocks are pressed together more and more tightly (i.e., increasing the normal force). These forces are converted to stress values when divided by the contact area.

When the shear stress required to cause sliding is plotted versus the normal stress, a simple graph is obtained as shown on the attached sample test result. Over limited portions of the graph, the relationship between shear strength and normal stress is assumed to be linear, hence linear equations are fitted to the data. The stress form of the shear strength equation is thus:

$$\tau = c + \sigma_n(\tan \phi)$$

where:

τ = shear strength	c = cohesion
σ_n = normal stress	ϕ = friction angle

The values are all in stress units, such as psf or kPa, except for the friction angle. For different ranges of σ_n, slightly different values for **c** and ϕ may provide the best fit.

For totally discontinuous surfaces, such as fractures containing no intact rock or mineral cement or fracture healing, the intercept of the line with the shear stress axis represents the ***cohesion*** of the surface, and the slope of the line indicates the ***friction angle*** of the surface.

Cohesion (c) may be thought, of in the above case, as the result of a natural "stickiness" of the rock due to the surface chemistry of the minerals. Essentially, it is the shear stress required to make the surfaces slide past each other if they are in full contact but have zero normal force pressing them together. For totally discontinuous hard rock surfaces, cohesion is usually very small and is often treated as being zero. When finding the best fit to the laboratory data over a specific range of normal stresses, cohesion may actually appear to be negative.

Friction angle (ϕ) is the component of shear strength that increases as normal stress increases. The rate of increase in strength is indicated by the slope of the line within various ranges of normal stress. It can be shown mathematically that for cases where cohesion equals zero, the friction angle represents an ***angle of repose*** of the material. That is to say, if the discontinuity dips less steeply than the friction angle, sliding will not occur unless additional forces act. And, if the discontinuity dips more steeply than the friction angle, sliding will occur even without additional forces.

Roughness of discontinuity surfaces also plays an important role. Smooth surfaces, such as planar jointing or saw cuts in the lab will have lower shear strength than rough irregular surfaces. Various methods are used to account for the effects of roughness. These include applying joint roughness coefficient (JRC) values based on observations of the surfaces (Barton, 1973), increasing the ϕ value by an amount ***i*** (up to 15°), based on surface measurements (Patton, 1966), and running direct shear tests on the actual natural discontinuity surfaces.

<u>Shear Strength Determination by Pull Testing</u>:

Pull testing is a simple procedure for estimating the shear strength values of discontinuities for some applications by placing one rock sample on another, loading them with weights, and pulling on the top sample with a line attached to a scale until sliding takes place (see attached photographs). Variations include inclining the discontinuity surface to take advantage of gravity enhanced sliding, however the equations become slightly more complicated in that case. Tests may be performed on regular field samples as well as rock core.

The author uses the following procedures for conducting pull tests:

1. Calculations are made to determine the approximate actual normal stresses on the discontinuities in question at the site being studied. It is important to run the lab tests in the range of the normal stresses to be encountered in the field. If the site stresses are extremely high, it may become necessary to have the tests run in a conventional shear box or direct shear machine.

2. For comparison, tests are performed on both natural discontinuity surfaces and on saw cut surfaces. Saw cut surfaces provide an estimate of the lower limit of shear strength. Saw cut values, with Patton's 15^{O} (i) value added to them, provide a theoretical upper limit to shear strength. The natural surface values tend to fall somewhere in between.

3. The contact surface is traced onto a sheet of paper and digitized using a CAD (Computer Aided Drafting/Design) program in order to ascertain the contact area in square inches or square feet. This is needed to convert the forces to stresses by dividing by the contact area.

4. The bottom sample is leveled and secured by clamping or by wedging it into place in a sand box. The upper sample is placed on top, a line is looped around it and attached to a spring scale. Weights are added and the force required to cause sliding is recorded.

5. The forces are converted to stresses and plotted using a computer spread sheet. Linear equations are fit to the data also using the computer spread sheet.

A sample test result is attached. Once the values are obtained, they may be used in safety factor calculations using limit equilibrium theory. If very small or negative values of cohesion are obtained during the testing, then cohesion is generally assumed to equal zero.

References

Barton, N.R., 1973. Review of a new shear strength criterion for rock joints. *Engineering Geology*, Elsevier. Vol. 7, pages 287-332.

Patton, F.D., 1966. Multiple modes of shear failure in rock. *Proc. 1st International Congress of Rock Mechanics*. Lisbon, Vol 1., pages 509-513.

Cluster 3 is the most **significant** cluster in terms of both population and DSI. The discontinuities of this cluster are bedding planes. It is no surprise; therefore, that even small railroad cuts not far away are severely affected by plane failures, where such cuts parallel the bedding strike as seen in Figure 11.

Cluster 1 is the most **critical** cluster in the highway slope. It dips directly out of the slope face, and it contains at least one discontinuity with a high DSI value. A plane failure involving Cluster 1 is highly likely along the roadway.

Finally, in recent years workers have noted that plane failures are not likely unless the discontinuity dips almost directly out of the slope face. The portion of the critical zone that lies within 20° (plus or minus) of the slope face dip direction is considered most vulnerable. Outside of that 20° zone, discontinuities disappear into the slope such that they often lock themselves in. Those discontinuities cannot be totally ignored; however, because other discontinuity sets may provide release surfaces for them, as in wedge failures.

2. Wedge Failures

Stereonet analyses for potential wedge failures are similar to stereonet analyses for plane failure. In order for a wedge failure to occur, the line made by the intersection of the planes creating the wedge must plunge more steeply than the friction angle and less steeply than the dip of the slope face. Plus, the line of intersection should daylight from the slope face. To test for these conditions, a single great circle may be chosen and plotted on the stereonet to represent each cluster. If any of the great circles intersect other great circles within the crescent-shaped critical zone then the conditions are met and a wedge failure is kinematically possible (Figure 12). The intersection point provides the plunge and trend of the line of intersection and is read from the plot in the same way as dip and dip direction.

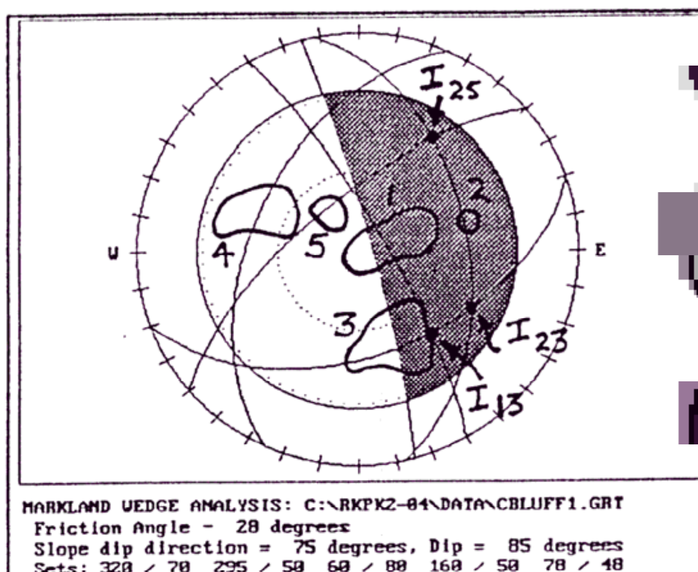


Figure 12. Markland's test for wedge failures at Cedar Bluff. Intersections of clusters 1&3, 2&3, and 2&5 fall within the critical zone. Dip vector clusters are outlined.