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Introducing CPILLAR

CPILLAR is a quick, interactive and simple to use analysis tool for evaluating the stability of surface or underground crown pillars, and laminated roof beds.

Some of the modelling and analysis features currently incorporated in CPILLAR 3.0 are:

- three different limit equilibrium analysis methods — Rigid or Elastic plate analysis, and Voussoir (no tension) plate analysis.
- statistical analysis of failure probability, by entering standard deviations for material and loading parameters.
- failure modes include Shear, Elastic or Gravity buckling, and compression.
- two lateral stress options — Gravity or Constant.
- three shear strength options — Hoek-Brown, Mohr-Coulomb, or Hoek-Brown with m and s estimated from rock mass rating and intact m .

CPILLAR provides an integrated CAD based graphical environment for data entry and 3D model visualization. With CPILLAR, you can easily create and visualize a roof or crown pillar model, calculate safety factors and failure probabilities, and interpret the results.

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CPILLAR Manual

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Dr. E. Hoek, for his development of the original CPILLAR program. The applicability of CPILLAR to practical mining engineering problems has been greatly enhanced by his involvement.

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Mark Diederichs, currently at the Geomechanics Research Centre in Sudbury, Ontario, for his refinement of the Voussoir analysis technique, which has been incorporated in CPILLAR 3.0. Further information on the latest Voussoir analysis improvements can be found in: Hutchinson and Diederichs, "Cablebolting in Underground Hard Rock Mines", Geomechanics Research Center Report.

The interface for CPILLAR is based on the FEINT user interface package (version 3.0) developed by Brent Corkum, Rock Engineering Group, University of Toronto, with funding from the Mining Research Directorate and the Rock Engineering Group.

Disclaimer

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

Hardware Support

CPILLAR supports the following hardware:

- IBM PC/XT/286/386/486/Pentium or compatible
- Graphics Display Adapters:
 - Video Graphics Array (VGA)
 - Enhanced Graphics Adapter (EGA)
 - Colour Graphics Adapter (CGA)
 - Hercules Monochrome Display Adapter
 - ATT 400 Series, Compaq Plasma
 - VESA Super VGA
- Microsoft or Logitech Mouse and compatibles (not required)

- 80x87 math coprocessor (not required)
- Printers:
 HP Laserjet, Laserjet III, Laserjet IV
 HP Paintjet, Paintjet XL, Paintjet XL300
 HP Deskjet, Deskjet 1200C
 Epson 9 and 24 Pin

Suggested minimum configuration:

80386 / VGA / 80387 / Mouse

Hard Disk Installation Procedure

CPILLAR is distributed with a installation program. To install CPILLAR, insert the CPILLAR disk into the A: or B: drive. Switch to that drive and type INSTALL.

Example Installation Process (installed from the A: disk drive)

```
C:\>a:
```

```
A:\>install
```

Various files will now be contained in your CPILLAR directory, including:

cpillar.exe	The CPILLAR program
cpillar.uid	User identification file, contains registration information
readme.txt	Document file containing up to date information on your current version of CPILLAR. Please read it.

Running CPILLAR

To run the program, type CPILLAR at the DOS prompt. You should see the start-up screen shown in Figure 1.1.

If you wish to run CPILLAR from a directory other than the installation directory, you must place the CPILLAR directory in your path:

```
PATH=C:\DOS;C:\CPILLAR;
```

CPILLAR will automatically detect the graphics card you are using with your computer and use the mode with the highest resolution on your video card. However, a variety of command line options are available if the user wants to force the program to operate in a specific graphics mode. The syntax and command line options for CPILLAR are:

Syntax: CPILLAR [options] [filename]

The graphics options [options] are:

```

/C      CGA (640 x 200) 2 colour mode
/E      EGA (640 x 350) 16 colour mode
/H      HERCULES (728 x 348) monochrome mode
/M      MCGA (640 x 480) 2 colour mode
/P      Monochrome emulation for all display adapters
/I      Reverse Monochrome emulation for all display adapters
/T      ATT card (640 x 400) 2 colour mode
/1      Super VGA (800 x 600) 16 colour mode
/V      VGA (640 x 480) 16 colour mode

```

Run CPILLAR with the /P command line option, for black and white screen captures.

The /P option is particularly useful when you want a black and white screen capture or wish to work in a monochrome environment on a colour or gray scale display. The /I option should be used when you want to work in reverse black and white mode (for Windows screen captures).

You may also choose to include a filename at the DOS prompt when running CPILLAR. This filename MAY INCLUDE a path and must follow a *space* after CPILLAR /[options]. If no filename is given in the command line, then use *Read File* in the main menu to load a file.

To display information about the command line options, type *cpillar /?* at the DOS prompt.

A note on Super VGA Support

The VESA Super VGA mode 800 x 600, 16 colours is supported. To run the program in this mode, you may use the /1 command line parameter (ie, CPILLAR /1), or set the environment variable SVGA to a value of 1 by placing the following line in your autoexec.bat file:

```
SET SVGA=1
```

If the program hangs in this mode, you might require a VESA driver for your display adapter to be loaded first.

Old CPILLAR Data Files

CPILLAR 3.0 will *not* read data files from any previous versions of CPILLAR (1.0, 1.2 or 2.0). Simply re-enter the data using the appropriate analysis option of CPILLAR 3.0. Use the RIGID analysis option for an equivalent of the CPILLAR 1.2 analysis, and the ELASTIC or VOUSOIR options for an equivalent of the CPILLAR 2.0 analyses.

CPILLAR Screen Layout

When running CPILLAR, the first screen presented to the user is the title screen shown in Figure 1.1. The screen is comprised of five independent sections, each of which contains important information about the program.

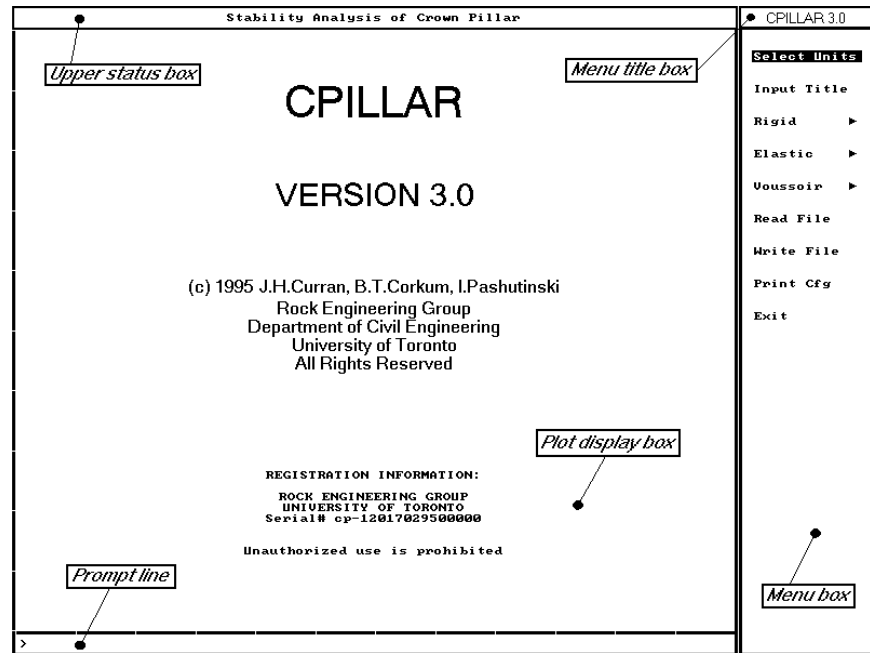


Figure 1.1: The CPILLAR start up screen.

Upper status box

The *upper status box* normally contains several pieces of information, concerning cursor location, grid and snap settings etc. in other programs available from the Rock Engineering Group at U of T. However, in CPILLAR these options are not required, so the upper status box is used only for displaying the title of the model.

Prompt line

The *prompt line* is used for certain text input, and also contains important instructions and helpful hints as you move through the options in CPILLAR. When in doubt about an option, read the prompt line. *Note: if you include a path when entering input or output filenames using Read File or Write File, the prompt line will scroll to allow up to 80 characters to be entered.*

Menu title box

The title of the *menu* in which you are working is displayed in the *menu title box* – in this case the CPILLAR main menu.

Menu box

The *menu box* displays the options contained in each menu – in this case, (Figure 1.1) the main menu is shown. Selecting any of the options by moving the cursor to the appropriate button and pressing **<Enter>** or the *left mouse button*, will activate the option or take you to the sub-menu that the button represents. Buttons which lead to sub-menus (the three analysis options) are identified with a triangular arrow symbol ►.

Plot display box

The *plot display box* is used for:

- graphical display of model data and analysis results,
- pop-up windows for interactive input and editing of data,
- cursor selection of input and output files.

Throughout this manual, the *plot display box* may also sometimes be referred to as the *viewing region* or *display region*.

If the user has entered a filename at the command line, the plot display box will show a 3D perspective view of the user's model, instead of the start-up screen text shown in Figure 1.1.

Using the Menu System

CPILLAR uses a sidebar tree structured menuing system for user interaction. Select an option by moving the highlighted menu bar with the keyboard arrow keys or by sliding the mouse up and down, until you are highlighting the option you wish to select. Press **<Enter>** or the *left mouse button* to select the option.

Use the **Home** and **End** keys, or the **right mouse button** to quickly toggle between the first and last options in a menu.

The *Home* and *End* keys will take the menu bar to the top and bottom of a menu respectively. The *right mouse button* will also take you immediately to either the top or bottom of a menu. In addition, each menu is actually a closed loop, so that the first item in a menu can be directly accessed from the last item, and vice versa.

Selecting the *Return* option in the analysis sub-menus will RETURN you to the main menu. By clicking the *right mouse button* (to highlight *Return* at the end of a sub-menu) and then the *left mouse button* (to select *Return*), the user can rapidly RETURN to the main menu.

Hot key

Use the <Alt X> keyboard combination to exit the program immediately from any menu.

The <Alt X> keyboard combination can be used as a short cut to EXIT the program (without saving) from any menu.

After executing a particular option you may notice that the cursor will jump to another option in the *menu box*, or the *plot display box*. This is to indicate the most common but not necessarily mandatory next step. In particular, when a CPILLAR file is read in, the most recent analysis method used on the model will be highlighted in the main menu.

Moving the cursor

Move the cursor with the mouse if you have one. Normally, the *left mouse button* will 'select' an item.

When entering data in the popup windows, the *keyboard arrow keys* will also move the highlighted box around the popup menus. Usually the <Enter> key is used to 'select' an option or item, and the <Esc> key is used to 'escape' from the option in use.

When using the *Crop Image* option for screen captures, holding down the *left Shift key* while using the arrow keys will result in larger cursor jumps. Holding down the *right Shift key* will move the cursor pixel by pixel.

Hot Keys

Two hot key combinations are available in CPILLAR:

<Alt X>	Exit CPILLAR immediately, from any menu, without saving.
<Ctrl P> or <Ctrl O>	Dump the screen to a printer, or PCX file. User specifies either <Ctrl P> or <Ctrl O> as the active hot key combination, in <i>Print Cfg</i> menu.

Main Menu

The first screen presented by CPILLAR is the title screen shown in Figure 1.1. The eight menu items available from this screen constitute the *main menu* – *Select Units*, *Input Title*, *Rigid (Analysis)*, *Elastic (Analysis)*, *Voussoir (Analysis)*, *Read File*, *Write File*, *Print Cfg*, and *EXIT*. These are briefly described below.

Select Units

Select Units allows the user to work with either **metric** or **imperial** units. The *Select Units* popup window is shown in Figure 1.2 below. Pressing <Enter> or clicking on the highlighted box with the mouse will toggle the choice between **metric** and **imperial**. Selecting *Save* will save the chosen option, and return the user to the main menu. Default unit system is **metric**.

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

Select Units	
Select Metric / Imperial :	Metric
Metric units	Imperial units
-----	-----
Metres	Feet
MN / m3	lb / ft3
MPa	psi
Save [ALT-S]	Abort [ALT-A]

Figure 1.2: The *Select Units* popup window.

Input Title

To assign a specific title to a model (other than the default title which appears at the top of the screen), select *Input Title* from the main menu, and the prompt line will display:

> Title:

Type in a title on the keyboard and press <Enter>. This title will appear in the upper status box of the screen and will also be written to the output file. A job title is useful whenever the screen is being captured for a printout.

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

Analysis Options

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

The three analysis options of CPILLAR – RIGID, ELASTIC and VOUSSOIR analyses – are accessed through these three options of the main menu. Selecting one of these options leads to the corresponding sub-menu, allowing the user to input relevant data and perform the stability analysis.

The subsequent chapters of this manual cover the three analysis options in detail, including data input, background theory and applicability of each method, stability calculations, and some example problems.

Read File

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

This option retrieves a CPILLAR file. Selecting *Read File* will list all CPILLAR files in the plot display area, and the prompt line will show:

> Input filename or select w/ mouse []:

The CPILLAR filename is entered by typing the name of the file, *without* the *.cpl* filename extension, on the prompt line, or by positioning the cursor over the desired filename on the screen and selecting it with the *left mouse button*.

If there is already a model displayed when you select *Read File*, you will see:

Current Model Will Be Destroyed, Continue? : YES NO

Selecting *Yes* will clear the screen of the existing model, allowing a new file to be read in as described above.

Write File

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

This option saves the current model as a CPILLAR file, with a *.cpl* filename extension. On selecting this option a list of existing CPILLAR files will be displayed in the plot display area and the prompt line will display:

> Output filename or select w/ mouse [current file.cpl]:

When working with a new model (or to rename an existing one), type a new filename in the prompt line box, *without* the *.cpl* filename extension.

When working with an existing file, the current filename will appear in the prompt line, and the user can select this by pressing *<Enter>*. Alternatively, position the cursor over the desired filename on the screen and select it with the *left mouse button*. Before a file is overwritten, a pop-up prompt will appear:

File Exists, Overwrite? : YES NO

Selecting *Yes* will overwrite the file with the new model.

Printer Configuration

CPILLAR
Select Units
Input Title
Rigid ►
Elastic ►
Voussoir ►
Read File
Write File
Print Cfg
EXIT

CPILLAR allows for the capturing of the screen to various printers and PCX format files. To capture a screen you must first configure the program for the proper printer using the *Print Cfg* option. The *Print Cfg* option of CPILLAR is found in the main menu as well as the three analysis sub-menus. When this option is selected, the pop-up menu shown in Figure 1.3 is displayed which allows the user to select various printer types, as well as print options.

PRINTER SETUP	
Printer Type	HP Laserjet III
Reverse White	YES
Shading	ON
Hot Key	<CNTRL P>
Orientation	LANDSCAPE
Printer Port	LPT1
Width (in)	6
Left Margin (in)	1
Top Margin (in)	1
Crop Image	YES
Dump to PCX file	NO
Save [ALT-S] Abort [ALT-A]	

Figure 1.3: Print Configuration menu.

Chosen settings are saved permanently (even after exiting the program), so it is not necessary to reconfigure *Print Cfg* each time the program is started. *Print Cfg* is only required if the current print configuration settings are to be altered.

Screen captures used in CPILLAR have been tested in CGA, EGA, VGA, and SUPER VGA 800x600 graphics modes. The following options can be toggled through their various selections via the *Print Cfg* option:

Printer Type – This option allows the user to select the type of printer they will be using. The printers supported by CPILLAR are:

HP Laserjet	HP Paintjet	HP Deskjet
HP Laserjet III	HP Paintjet XL	HP Deskjet 1200C
HP Laserjet IV	HP Paintjet XL 300	Epson 9 and 24 Pin Printers

Reverse White – This option allows the user to select whether *white text* is printed as *white* or *black*. All *images* are printed with a white background.

Shading – This option allows users with black and white printers to print colours as shaded patterns.

Hot Key – This option allows the user to toggle between two *hot key* combinations, <Ctrl P> and <Ctrl O>. Pressing the *hot key* combination initiates the printing process to the designated printer or PCX file. When you press the hot key combination to print the screen, you will hear two “beeps” to indicate the beginning and the end of the printing process.

Orientation – This option allows the user to toggle between two orientations, *landscape* and *portrait*. The *portrait* option prints the screen in a traditional vertical page format. The *landscape* option prints the screen aligned with the long axis of the page (ie, at 90° to the *portrait* option).

Printer Port – This option allows the user to toggle between three printer ports, LPT1, LPT2 and LPT3, in order to select which port the image is to be sent to.

Width, Left Margin and Top Margin – These three options allow the user to vary the width of the image and the spacing of the margins of the screen to be printed. Note that the width *always* refers to the width aligned to the short direction of the paper, in both the landscape and portrait orientations.

Crop Image – This useful option allows cropping and printing of any portion of the screen. When the *Crop Image* option is chosen, a window will be activated at the time the printing process is started (ie, after pressing the hot key combination). Any portion of the screen can be cropped by using the mouse or the keyboard arrow keys to locate the upper left and lower right corners of the window. To enter a window corner and toggle to the opposite corner, use the *left mouse button* or <Enter> on the keyboard. When the desired location of the box has been determined, hit <Esc> or click the *right mouse button* to start printing the cropped image. **HINT:** The box location can be adjusted very precisely by holding down the *right shift key*, and using the *keyboard arrow keys* – this will move the edges of the box in very small (single pixel) increments.

HINT: The box location can be adjusted very precisely by holding down the right shift key, and using the keyboard arrow keys, to move the edges of the box in single pixel increments.

Dump to PCX File – This option allows you to save the screen image to a file in PCX format instead of sending it to a printer. This is useful for importing graphics images into word processor documents or drawing programs. With the *Dump to PCX File* option, the user can toggle between **OFF**, **ON** and **REVERSE**. To save an image to a file, turn the PCX file option to **ON**. Use the **REVERSE** option to capture the PCX image with a white background. To capture the image to a PCX file, press the hot key combination as you would to send the image to a printer. The file will be saved with the following preset filename format: **screen?.pcx**. The ? will be a number that starts at 1 and increments by 1 depending on how many PCX files already exist in the current directory – ie, screen1.pcx, screen2.pcx, screen3.pcx, etc. In some cases, programs reading in PCX files dumped with a white background, will display or print the background as grey. To ensure a white background, read the PCX file into a package such as Pizazz Plus for Windows, and **Save As PCX Black & White**.

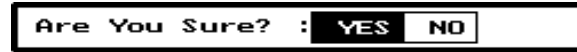
To capture an image to a PCX file, press the **hot key** combination as you would to send the image to a printer.

Use the **REVERSE** option to capture the PCX image with a white background.

CPILLAR
Select Units
Input Title
Rigid ▶
Elastic ▶
Voussoir ▶
Read File
Write File
Print Cfg
EXIT

Exit

When finished working with CPILLAR, selecting EXIT from the main menu will quit the program. If you are in one of the analysis sub-menus, select RETURN at the bottom of the sub-menu to return to the main menu. Before exiting CPILLAR, a pop-up prompt will ask:



Selecting *Yes* with the mouse, or typing 'y' will quit the program.

Recall that you can immediately exit the program from any menu by pressing the hot key combination **<Alt X>**.

CPILLAR Analysis Methods

Three different analysis methods are presented in CPILLAR 3.0 for the assessment of crown pillar and roof stability: **RIGID** or **ELASTIC** plate analyses, and **VOUSSOIR** (no tension) plate analysis. The failure modes and main assumptions for each analysis method are outlined below.

RIGID* ANALYSIS
<p><u>Failure mode considered:</u></p> <p>(1) Shear (vertical slippage at abutments).</p> <p><u>Main assumption:</u></p> <p>A simple 'falling block' analysis, where the crown pillar or roof beam is treated as a rigid block. Elastic properties are not considered.</p> <p><u>Applicability:</u></p> <p>Low, medium or high confining stresses. Any span / depth ratio is valid.</p> <p>(*RIGID analysis option of CPILLAR 3.0 is equivalent to CPILLAR 1.2 program, with the addition of some new functionality.)</p>

ELASTIC ANALYSIS
<p><u>Failure modes considered:</u></p> <p>(1) Shear (vertical slippage at abutments). (2) Elastic buckling.</p> <p><u>Main assumption:</u></p> <p>Roof behaves as an elastic fixed beam or plate, with span equal to the shorter of the x and y dimensions.</p> <p><u>Applicability:</u></p> <p>Low, medium or high confining stresses. Span / depth ratios < 3 not recommended.</p>

VOUSOIR ANALYSIS
<p><u>Failure modes considered:</u></p> <ul style="list-style-type: none"> (1) Shear (vertical slippage at abutments). (2) Arch snap-thru (buckling due to gravity). (3) Localized crushing failure. <p><u>Main assumptions:</u></p> <ul style="list-style-type: none"> (1) Roof cannot sustain tensile stresses, and supports itself primarily through formation of a parabolic compression arch, as it deflects. (2) Deflection of the beam occurs before slippage at the abutments. Stability against slippage is determined after the compression arch develops. (3) Initial lateral stress resulting from in-situ stress and/or excavation geometry is not considered in this analysis. The beam is assumed to be initially stress free. (4) Cross-cutting structure is angled at significantly less than the minimum angle of friction assumed for the jointed surfaces. <p><u>Applicability:</u></p> <p>Low confining stresses. Span / depth ratios < 3 not recommended.</p>

A Note on Terminology

Throughout this manual, the terms **pillar**, **roof**, **roof beam** and **roof plate** may be used, depending on the context, to refer to the basic entity being analyzed (ie, the **rock** of dimensions **x**, **y** and **z**).

A **pillar** refers mainly to models with a low span/depth ratio. **Beam** and **plate** refer to models with higher span/depth ratios, a **beam** referring to a long excavation (one lateral dimension much larger than the other), and a **plate** referring to a square or rectangular excavation (both lateral dimensions the same order of magnitude).

For convenience, the term **pillar** is used most frequently in this manual.

Analysis Menu

ANALYSIS
Input Values
Calculate
Theory
Reset
Print Cfg
RETURN

Selecting one of the 3 analysis options from the main menu will bring up the analysis sub-menu, shown in the sidebar at left. This menu is the same for all three analysis methods (the actual name of the analysis – RIGID, ELASTIC or VOUSOIR – will appear in the *menu title box*). Its options are briefly outlined below.

Input Values

All data relevant to the stability analysis is entered by selecting *Input Values*. A pop-up window will appear, allowing the user to enter all geometry, material, loading and strength parameters. This is discussed in detail for each analysis method in the next chapter.

Calculate

After all necessary input data has been entered using *Input Values*, selecting *Calculate* will perform the stability analysis, and display the results in the plot display region. If any required data is missing or incorrect, various warning messages may be displayed before calculation can proceed.

Theory

For an outline of the assumptions and failure modes involved with each analysis method a *Theory* button is provided. This will display popup information which the user can scroll through for on-line clarification of the applicability and scope of each analysis method.

Reset

To erase all current data and start with a clean slate, a *Reset* button is provided, so a user can enter a new model from scratch. Before data is erased, a pop-up prompt will appear:

Current Model Will Be Destroyed, Continue? : YES NO

Selecting 'yes' will reset all appropriate values to zero (or initial) values, however 'Strength Criterion' and 'Lateral Stress' types are left at their most recent selections, since a user is probably working with certain strength and stress criteria.

Print Cfg

This is the same *Print Configuration* option available in the CPILLAR main menu – it is available from within the analysis menus for extra convenience. For a complete description of the *Print Cfg* options, see the *Print Configuration* section at the end of the first chapter.

CPILLAR Input

Geometry

Since entry of model dimensions is identical for all three analysis methods, this is discussed first.

- A pillar is defined by its **length**, **width** and **thickness**, or **x**, **y** and **z** values. These are the first 3 items entered in the *Input Values* popup window for all three analysis methods. (Depending on the relative magnitudes of x, y and z, the term **pillar**, **beam** or **plate** may be most applicable, as described at the end of this section. For convenience, the term **pillar** is used most often throughout this manual.)
- In addition, a **thickness** of overburden can be added above the pillar.
- Finally, if the **height** of water is greater than the (pillar + overburden) thickness, the difference will appear as free water above the pillar. These situations are illustrated below.

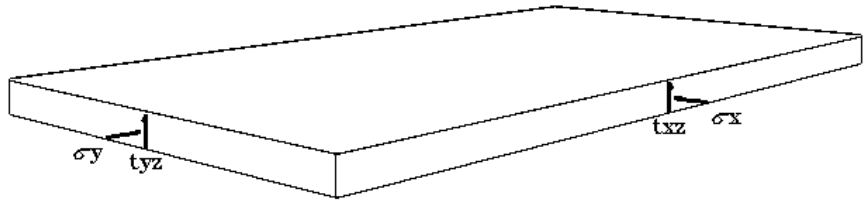


Figure 3.1: Plate with dimensions $x = 10$, $y = 20$, $z = 1$

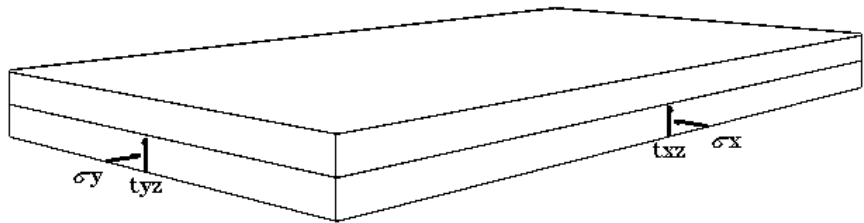


Figure 3.2: Same as Figure 3.1, with overburden thickness = 1 added.

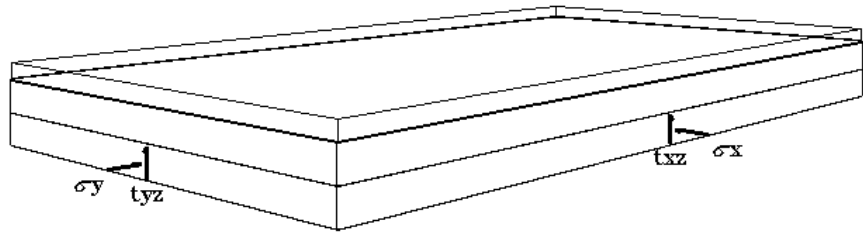


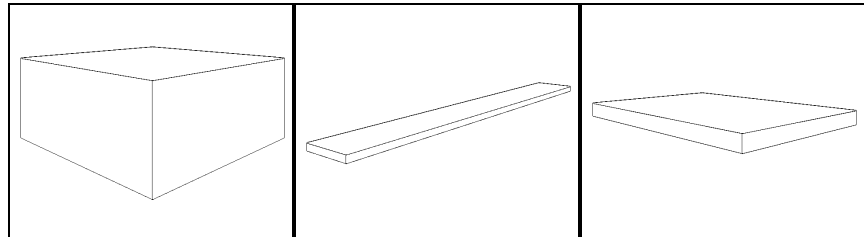
Figure 3.3: Same as Figure 3.2, with addition of water height = 2.5.

*Water **height** is measured from the **bottom** of the pillar.*

Note that the water **height** is measured from the **bottom** of the pillar, whereas the pillar and overburden thicknesses are entered as absolute values. This is because water pressure is taken into account if the pillar is specified as 'permeable', (RIGID and ELASTIC options only) therefore water heights less than the pillar thickness can be specified to account for the effect of water pressure on effective lateral stress.

If a water height **less** than the pillar (+ overburden) thickness is specified, the user will notice a line representing the water height, drawn on the model at the appropriate level. On a colour monitor, the pillar and overburden material will have different colours above and below the water table.

Pillars, Beams and Plates



Pillar

Beam

Plate

*Low span/depth ratio
= **PILLAR***

Depending on the relative magnitudes of x, y and z, the term **pillar**, **beam** or **plate** will most correctly describe the geometric model.

- A **pillar** refers to a model with a **low** span/depth ratio, the **span** being the shorter of the x and y dimensions.
- A **beam** refers to a model with one of the lateral dimensions substantially longer than the other, and a fairly high span/depth ratio (eg. > 3). Note that the **beam span** is the **short** lateral dimension.

High span/depth ratio

$x \gg y$ or $y \gg x$

= **BEAM**

x and y similar magnitude

= **PLATE**

- A **plate** refers to a model where both lateral dimensions are of similar magnitude, and again a fairly high span/depth ratio (eg. > 3).

For convenience, the term **pillar** is used most often throughout this manual.

To model the roof of a long excavation (a **beam**), make one lateral dimension much longer than the other (eg. $x = 10$, $y = 100$). A factor of 10 should suffice, although the user can specify any realistic dimensions (eg. $x = 10000$, $y = 10$).

Note that the 'long' and 'short' lateral dimensions can be **either** the x or the y dimension. Make sure the corresponding lateral stresses (see next section) are consistent with the chosen x and y directions (see Figure 3.5).

Statistics

CPILLAR will calculate **failure probabilities** if the user chooses to enter **standard deviations** for the strength and loading parameters. The calculated failure probability is based on:

- a **normal distribution** of input parameter values, and
- a **normal distribution** of calculated safety factors.

See the next chapter, *CPILLAR Output*, for further discussion of statistical analysis.

The entry of standard deviations is optional. For a deterministic analysis of safety factors, simply leave the default zero values of standard deviation.

Rigid Analysis Input

To enter parameters for a RIGID analysis, select *Rigid* from the main menu, and *Input Values* from the RIGID analysis sub-menu. The pop-up window shown in Figure 3.4 will appear.

Numerical values are entered by moving the highlighted selection box to the desired location using the mouse or the keyboard arrow keys. Type in a value, and press <Enter> to enter the value, or <Esc> to escape without entering a new value. The previous value will be reloaded if the user hits <Esc>.

Use the **Home** and **End** keys to quickly move the selection box to the top or bottom of the input menu.

Hints: a number can be typed in directly if the selection box is highlighted, pressing <Enter> beforehand is optional. Also, the *Home* and *End* keys on the keyboard will move the highlighted selection box to the top and bottom of the menu respectively.

Some of the menu items toggle through various selections, and are not used directly for numerical input. 'Is Pillar Permeable?' toggles between 'Yes' and 'No' and 'Lateral Stress' and 'Strength Criterion' toggle through various selections, which are explained in the following pages.

RIGID parameters			
Pillar X Dimension	(m)	0	
Pillar Y Dimension	(m)	0	
Pillar Thickness	(m)	0	
Rock Unit Weight	(MN/m3)	0.027	
Overburden Unit Wt	(MN/m3)	0.02	
Water Unit Weight	(MN/m3)	0.01	
Is Pillar Permeable?		No	
Lateral Stress		Gravity	
		mean	std dev
Water Height	(m)	0	0
Overburden Thickness	(m)	0	0
Horiz/Vert Kx		0	0
Horiz/Vert Ky		0	0
Strength Criterion		Hoek-Brown (RMR)	
		mean	std dev
Rock Mass Rating		0	0
Intact m value		0	0
Intact Strength	(MPa)	0	0
Save [ALT-S]		Abort [ALT-A]	

Figure 3.4: *Input Values* popup window for RIGID analysis.

Pillar Dimensions

Values must always be entered in these three boxes, for the **x**, **y** and **z** dimensions of the pillar. If zero values are entered, an error message will be displayed when attempting to *Calculate*.

For a RIGID analysis, there is no restriction on the span / depth ratio of the pillar, any realistic values of x, y and z can be entered. (For ELASTIC or VOUSSOIR analyses, span / depth ratios should be at least 3 for the analyses to be valid. The span / depth ratio is the minimum of the x or y values, divided by the z value.)

For further discussion of pillar geometry, see the previous section in this chapter.

Unit Weight

ROCK & OVERBURDEN – For convenience, default values of rock and overburden unit weight will appear, but the user can enter different values as required.

WATER – The default value which appears here cannot be changed by the user, it is defined by the unit system and will be either .01 MN / m³ or 62.4 lb / ft³, depending on which unit system the user has selected.

Is Pillar Permeable?

This option toggles between ‘Yes’ and ‘No’.

*Water height < pillar thickness has **no** effect if pillar is impermeable.*

NO – Water height **less than** the pillar + overburden thickness will have no effect on the model whatsoever. If water height is **greater than** the pillar + overburden thickness, then the weight of the free water will have an effect as an extra deadload on the pillar.

YES – Effect of water pressure on lateral effective stress will be taken into account. However, if water height is too high, negative effective stresses will result, and a warning message will appear when attempting to *Calculate*.

To toggle, highlight the box and press <Enter>, or select with the *left mouse button*.

Lateral Stress

This toggles between two options, **Gravity** and **Constant**. With the Gravity option, the user inputs horizontal / vertical stress ratios from which the lateral stresses are calculated (see below). With the Constant option, the user inputs the actual lateral effective stresses. The corresponding options in the input menu will change as this option is toggled.

Figure 3.5 illustrates the relations between the lateral and shear stress directions, and the pillar dimensions.

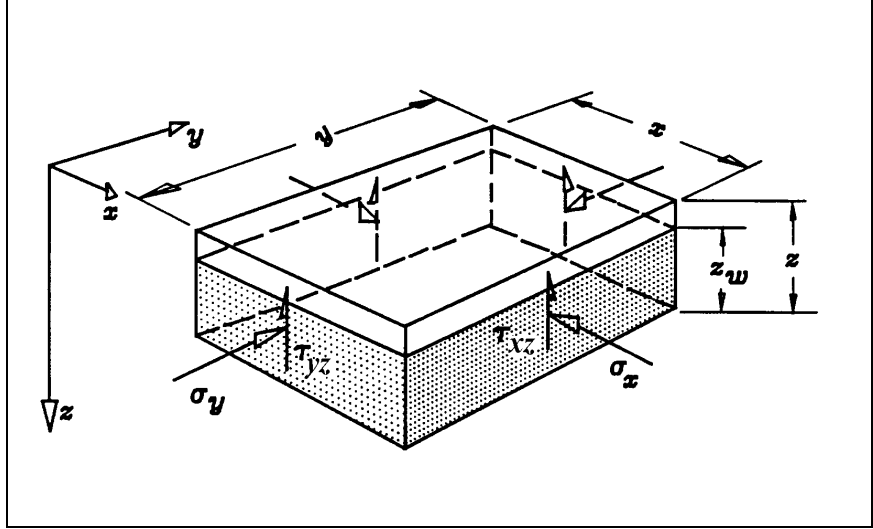


Figure 3.5: Relationship between stress directions and pillar dimensions.

Gravity

With this option, average lateral stresses are calculated based on the horizontal to vertical stress ratios, the pillar thickness, and the water height (if pillar is permeable), as follows:

$$\text{Lateral stress} = \gamma_r \cdot z \cdot K / 2 - \gamma_w \cdot z_w^2 / (2 \cdot z) \quad \text{Eqn 3.1}$$

where: γ_r = rock density

z = pillar thickness

K = horiz/vert stress ratio

γ_w = water density

z_w = water height

If water height is > pillar thickness, the water pressure component of the above formula is modified accordingly:

$$\text{Lateral stress} = \gamma_r \cdot z \cdot K / 2 - \gamma_w \cdot (z_w - z/2) \quad \text{Eqn. 3.2}$$

Note that Eqn. 3.2 allows the calculation of the water height which will produce zero effective stress (if pillar is permeable), as shown in Eqn. 3.3. If a water height greater than this is specified, negative effective stresses will result and calculation will not proceed, unless the user enters 'yes' at the warning prompt which will appear when *Calculate* is selected.

$$\text{Critical } z_w = (\gamma_r / \gamma_w) \cdot z \cdot K / 2 + z / 2 \quad \text{Eqn. 3.3}$$

Gravity lateral stress
*option should only be used
 for surface crown pillars.*

Since the vertical pressure is based only on the thickness of the pillar, it can be seen that this option is only strictly applicable for surface crown pillars. Only an average value of the lateral stress is calculated by this method, the true variation of field stress with depth is not considered. Therefore the **Gravity** option as presented in CPILLAR is actually a type of **Constant** stress option, which calculates an average lateral stress based on the thickness of the pillar, and the user input horizontal / vertical stress ratios.

Constant

This option allows the user to input the actual values of the lateral effective stresses in the x and y directions.

When using this option, water pressure will have no effect on the lateral stress, even if 'Is Pillar Permeable?' is toggled to 'Yes', since the user is already entering effective stresses.

Water Height

Unlike the overburden thickness, the water **height** is the height measured from the **bottom** of the pillar, so that water pressure can be taken into account if the pillar is specified as 'permeable'.

Depending on the relative water height, the permeability of the pillar, and the lateral stress option, various situations will arise:

If pillar is 'impermeable'

Water height < pillar + overburden thickness will have no effect.

Water height > pillar + overburden thickness will add a deadload due to weight of the free water.

If pillar is 'permeable'

Water pressure will reduce the lateral effective stress if the **Lateral Stress** option = **Gravity**. If the water height is more than about twice the pillar height, negative effective stresses will result, and a warning will be displayed when attempting to *Calculate*.

If water height > pillar + overburden thickness, and lateral effective stresses are **not** negative, then the weight of the free water will still add an extra deadload component to the pillar load.

If Lateral Stress option = Constant

Water height will have no effect on the lateral stress, since the user is already entering effective stresses. If water height > pillar + overburden thickness, then the deadload due to the weight of the free water will still be calculated.

Overburden Thickness

This is the absolute value of the overburden thickness, and is NOT measured from the base of the pillar, as is the water height (see above).

For illustrations, see the Geometry section earlier in this chapter.

Horizontal to Vertical Stress Ratios

Used with the **Gravity** lateral stress option. See above for details.

Horizontal Effective Stresses

Used with the **Constant** lateral stress option. See above for details.

*Note: the user should check that the input here corresponds with the definitions of the **x** and **y** pillar dimensions. Check Figure 3.5.*

*Make sure the lateral stress directions correspond to the **x** and **y** pillar dimensions – see Figure 3.5*

Strength Criterion

Three *Strength Criterion* options are available in CPILLAR for the calculation of the rockmass shear strength. Toggling the *Strength Criterion* button will allow entry of the appropriate parameters in the last three input boxes.

Hoek-Brown (RMR)

With this option, the Hoek-Brown strength parameters **m** and **s** are estimated from the **Rock Mass Rating** and the **Intact m Value** using the following equations (Ref. 1):

$$m = m_i \cdot \exp [(RMR - 100) / 14] \quad \text{Eqn. 3.4}$$

$$s = \exp [(RMR - 100) / 6] \quad \text{Eqn. 3.5}$$

Required parameters for calculation of shear strength using the **Hoek-Brown (RMR)** option:

Rock Mass Rating	Intact m value	Intact Strength
------------------	----------------	-----------------

The **Rock Mass Rating** being used here is Bieniawski's rock mass rating (RMR). Representative values are shown in Table 3.1 below (Ref. 1).

The **Intact m value** refers to the **m value for intact rock samples**, from which the **rockmass m value** is calculated.

The **Intact Strength** refers to the **unconfined uniaxial compressive strength of intact rock samples**.

Rock description	Rock Mass Rating
Intact Rock Samples	100
Very Good Quality Rock Mass	85
Good Quality Rock Mass	65
Fair Quality Rock Mass	44
Poor Quality Rock Mass	23
Very Poor Quality Rock Mass	3

Table 3.1: Correspondence of rock quality with Bieniawski's rock mass rating.

Hoek-Brown

With this option, the user enters the Hoek-Brown **rockmass** parameters **m** and **s** directly.

Required parameters for calculation of shear strength using the **Hoek-Brown** option:

Rockmass m value	Rockmass s value	Intact Strength
------------------	------------------	-----------------

The **Intact Strength** refers to the **unconfined uniaxial compressive strength of intact rock samples**.

Mohr-Coulomb

Shear strength will be calculated from the Mohr-Coulomb cohesion and friction angle parameters **c** and ϕ .

Required parameters for calculation of shear strength using the **Mohr-Coulomb** option:

Cohesion	Friction Angle	(* n/a)
----------	----------------	---------

(* **Intact Strength** is not required when using the Mohr-Coulomb *Strength Criterion* with a RIGID or ELASTIC analysis. For a VOUSOIR analysis, the **Intact Strength** is required to calculate the safety factor for localized crushing failure, and therefore it is a required parameter regardless of *Strength Criterion*.)

Elastic Analysis Input

To enter parameters for an ELASTIC analysis, select *Elastic* from the main menu, and *Input Values* from the ELASTIC analysis sub-menu. The pop-up window shown in Figure 3.6 will appear.

As all data input is identical to that for a RIGID analysis (with the exception of Rock Mass Modulus), see the previous section (**Rigid Analysis Input**) for information on the data input options. Only the items exclusive to the ELASTIC analysis *Input Values* popup window are discussed below.

ELASTIC parameters			
Pillar X Dimension	(m)	0	
Pillar Y Dimension	(m)	0	
Pillar Thickness	(m)	0	
Rock Unit Weight	(MN/m ³)	0.027	
Overburden Unit Wt	(MN/m ³)	0.02	
Water Unit Weight	(MN/m ³)	0.01	
Is Pillar Permeable?		No	
Lateral Stress		Gravity	
		mean	std dev
Water Height	(m)	0	0
Overburden Thickness	(m)	0	0
Horiz/Vert Kx		0	0
Horiz/Vert Ky		0	0
Strength Criterion		Hoek-Brown (RMR)	
		mean	std dev
Rock Mass Rating		0	0
Intact m value		0	0
Intact Strength	(MPa)	0	0
Rock Mass Modulus	(MPa)	0	0
Save [ALT-S]		Abort [ALT-A]	

Figure 3.6: *Input Values* popup window for ELASTIC analysis.

Rock Mass Modulus

In order to calculate the Euler buckling stress for the pillar, the user must enter a Rock Mass Modulus, at the bottom of the ELASTIC *Input Values* popup window. This is the only additional item, as compared with the RIGID analysis *Input Values* popup window.

Automatic calculation of rock mass modulus from RMR

When using the **Hoek-Brown (RMR)** strength criterion option, an extra feature has been added for convenience – the Rock Mass Modulus will be automatically calculated from the Rock Mass Rating, as soon as the user enters a value for the Rock Mass Rating. This calculation is based on the following empirical formula (Ref. 1):

$$\text{Rock Mass Modulus} = 1000 * 10^{(\text{RMR} - 10) / 40} \quad \text{Eqn. 3.6}$$

where RMR = Rock Mass Rating (Bieniawski's) and the units of Rock Mass Modulus are MPa. (If the unit system is imperial, the appropriate conversion is applied).

If the user enters a standard deviation for the Rock Mass Rating, a standard deviation for the Rock Mass Modulus will be calculated, based on the mean and standard deviation of the Rock Mass Rating.

If the user prefers to enter their own value of Rock Mass Modulus, the pre-calculated value can be changed by entering a new number in the usual fashion.

This feature is only available when using the **Hoek-Brown (RMR)** option. When using the regular **Hoek-Brown** option, or the **Mohr-Coulomb** option, no automatic calculation of modulus will take place. However, the user can utilize the automatic calculation feature of the Hoek-Brown (RMR) option, and then switch *Strength Criterion*, if desired.

Voussoir Analysis Input

To enter parameters for a VOUSSOIR analysis, select *Voussoir* from the main menu, and *Input Values* from the VOUSSOIR analysis sub-menu. The pop-up window shown in Figure 3.7 will appear.

As much of the input data is identical to that of the RIGID and ELASTIC input menus, see the previous two sections “Rigid Analysis Input” and “Elastic Analysis Input” for information on the data input options which are common to the analysis methods. Only the items exclusive to the VOUSSOIR analysis *Input Values* popup window are discussed below.

VOUSSOIR parameters			
Pillar X Dimension	(m)	0	
Pillar Y Dimension	(m)	0	
Pillar Thickness	(m)	0	
Rock Unit Weight	(MN/m ³)	0.027	
Overburden Unit Wt	(MN/m ³)	0.02	
Face Dip	(deg°)	0	
		mean	std dev
Overburden Thickness	(m)	0	0
Support Pressure	(MPa)	0	0
Strength Criterion		Hoek-Brown (RMR)	
		mean	std dev
Rock Mass Rating		0	0
Intact m value		0	0
Intact Strength	(MPa)	0	0
Rock Mass Modulus	(MPa)	0	0
Poisson Ratio		0.2	0
Save [ALT-S]		Abort [ALT-A]	

Figure 3.7: *Input Values* popup window for VOUSSOIR analysis.

Face Dip

For a VOUSSOIR analysis, the user can specify a dip angle (degrees from horizontal) for the excavation face (≥ 0 and < 90). Specifying an angle > 0 has the effect of lowering the effective gravitational driving force by a factor of $\cos(\text{dip angle})$. Other than this, the analysis procedure is the same as for a zero dip angle.

Note: If a dip angle > 0 is specified, this will **not** appear in the model which is drawn on the screen. This drawing will always appear ‘horizontal’ regardless of the dip angle specified.

Overburden Thickness

Specify an overburden thickness in the same manner as for the RIGID or ELASTIC analysis options. If the face dip is > 0 , estimate an effective overburden thickness along the same 'z' axis as the pillar thickness is being measured, since the overburden deadload gets multiplied by the same factor $\cos(\text{dip angle})$ as the pillar deadload.

Including Free Water in a Voussoir Analysis

Water height is not included in a Voussoir analysis, since external lateral stresses are not accounted for and therefore the effect of water pressure on effective stress is not an issue. However, free water can be included in a Voussoir analysis, by considering it as 'overburden' and entering an overburden density equal to the density of water. To include overburden **and** free water in a Voussoir analysis, simply enter an appropriate overburden thickness and density to create an equivalent deadload on the pillar.

Support Pressure

This allows the user to enter an effective support pressure perpendicular to the excavation face.

For example: 240 kN cables perpendicular to the face at 2 x 2 metres

$$= 0.24 \text{ MN} / 4 \text{ sq. m.} = 0.06 \text{ Mpa.}$$

Cohesion

When using **Mohr-Coulomb Strength Criterion** with **VOUSSOIR** analysis, **cohesion** = 0.

When using the **Mohr-Coulomb Strength Criterion** with a VOUSSOIR analysis, the **cohesion** is automatically set to zero, since by definition the roof is supporting itself through frictional resistance only. If the user attempts to enter a value for cohesion, a warning prompt will be displayed in the prompt line.

Intact Strength

For a VOUSSOIR analysis, the intact uniaxial compressive strength is used to calculate a factor of safety against localized crushing failure (see next chapter), therefore a value for Intact Strength must be entered regardless of the *Strength Criterion* used for the VOUSSOIR analysis. (In the RIGID and ELASTIC analyses, no Intact Strength value is required if the *Strength Criterion* is Mohr-Coulomb – it is only required for the Hoek-Brown shear strength calculations).

Poisson's Ratio

For the CPILLAR Voussoir analysis, the Poisson's Ratio is used when calculating the incremental shortening of the compression arch formed by a rectangular roof plate. A default value of 0.2 will appear, but this can be changed to any value ≥ 0 and ≤ 0.5 . Values between 0.2 and 0.3 are most typical.

CPILLAR Output

ANALYSIS
Input Values
Calculate
Theory
Reset
Print Cfg
RETURN

After all relevant data has been entered, select *Calculate* from the analysis menu in which you are working. If all input parameters are valid, results will be calculated and immediately displayed. Figure 4.1 illustrates a typical screen after *Calculate* has been selected.

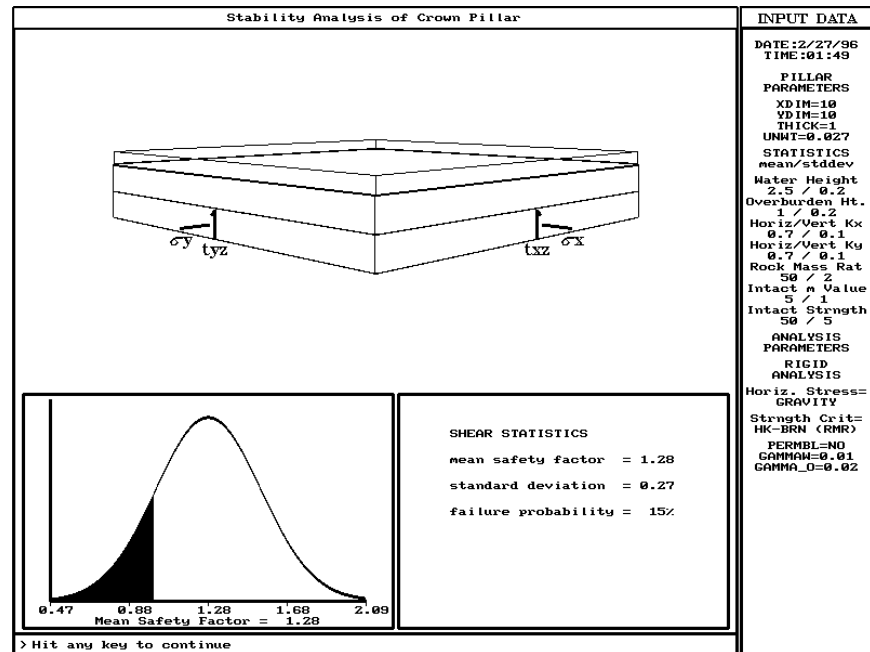


Figure 4.1: Typical display of results after selecting *Calculate*.

The display will include:

- a 3D perspective view of the model in the upper portion of the **plot display box**. In this case, a square pillar (10x10x1) is shown, with 1 metre of overburden and a water height = 2.5 metres.
- a normal distribution curve of safety factor, highlighting the area of the distribution below a safety factor of 1, in the lower left corner of the **plot display box**. The failure mode and numerical values of the mean, standard deviation, and failure probability, will be written in the lower right corner of the **plot display box**. In this case, the shear FOS results from a RIGID analysis are shown.
- a summary of all model and analysis parameters, in the **menu box** area on the right of the screen.
- a prompt in the **prompt line** to “Hit any key...”, to either return to the analysis menu, or see the results for another failure mode (RIGID, ELASTIC and VOUSOIR analyses will show results for 1, 2 and 3 failure modes, respectively).

Failure Probability Analysis

For the purposes of the CPILLAR limit equilibrium analysis, it is assumed that the pillar dimensions (defined by **x**, **y** and **z**), and the rock, overburden and water unit weights are known with a high enough degree of precision that they can be assigned unique values.

The other parameters are each defined by a **mean value** and a **standard deviation** in view of the high level of uncertainty associated with many of these parameters. It is assumed that the parameter values are **normally distributed** around the mean. By calculating the safety factor for all possible combinations of the statistical variables (see below), a likely **distribution of safety factor** is obtained, from which a **failure probability** can be calculated.

One method which can be used to investigate the distribution of safety factors is the so-called 'Monte Carlo' technique. The method used by CPILLAR is a simplified method of analysis known as Rosenbleuth's 'point estimate method', (Ref. 2). In this method, two point estimates are made for each random variable at fixed values of one standard deviation on either side of the mean (**mean \pm standard deviation**), and the limit equilibrium analysis is carried out for every possible combination of point estimates. This produces 2^m solutions, where 'm' is the number of normally distributed variables involved.

EXAMPLE:

If a RIGID analysis is carried out with both **water height** and **overburden** values entered, then the limit equilibrium analysis will contain **seven** random variables which are assumed to be normally distributed, and hence 128 values of the safety factor are obtained from this process ($2^7 = 128$). The mean and standard deviation of the 128 values of safety factor are then calculated, and from the knowledge that the factor of safety is also normally distributed (Ref. 3), the normal distribution for a range of ± 3 standard deviations on either side of the mean can be calculated. This is shown in Figure 4.2.

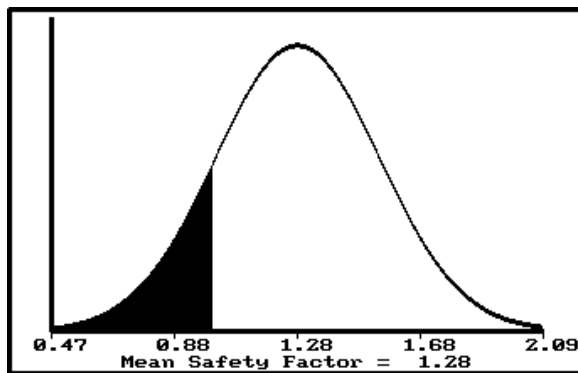


Figure 4.2: Normal distribution of safety factor.

The **probability of failure** is given by the ratio of the area under the normal distribution curve for factor of safety values from $-\infty$ to **1** (shown shaded) to the total area under the curve from $-\infty$ to $+\infty$.

Not all of the variables are required in each analysis, and so the number of combinations analysed will vary. For instance, if **water** and **overburden** are **not** part of a model, then only 5 random variables will be involved in a RIGID analysis, and therefore the distribution will be based on $2^5 = 32$ safety factors instead of $2^7 = 128$.

Depending on whether **water** (ELASTIC and RIGID analyses), **overburden**, and **support pressure** (VOUSOIR analysis) are included in a model, the number of possible safety factors calculated for each analysis method may vary as shown in the table below:

Analysis:	RIGID	ELASTIC	VOUSOIR
Possible point estimate combinations:	32, 64 or 128	64, 128 or 256	32, 64 or 128

Negative numbers in safety factor distribution

In some cases, negative numbers will appear at the left end of the normal distribution curves of safety factor.

This occurs when the safety factor standard deviation is high, specifically, when the **mean safety factor is $< 3 * (\text{standard deviation})$** .

This does **not** indicate that negative safety factors have been calculated.

Sensitivity Study of Safety Factor

*To calculate a unique factor of safety, enter **zero** values for all standard deviations.*

CPILLAR can be used to determine the safety factor distribution and probability of failure, as discussed above, or it can be used to calculate a unique factor of safety by entering zero values for all the standard deviations. This method can be useful when it is desired to explore the sensitivity of the factor of safety to changes of each of the variables in turn.

To investigate the sensitivity of safety factor to pillar thickness **z**, the user must enter different values and *Calculate* for each value. Even though the pillar thickness is often not a precisely known quantity, no option has been made available to input a standard deviation for the pillar thickness, to ensure that the effect of this fundamental parameter does not get 'lost' in the statistical analysis.

Rigid Analysis* Failure Mode

Only one failure mode
considered in a RIGID
analysis:

SHEAR

Shear

This is the only failure mode considered in a RIGID analysis. The crown pillar or roof beam is treated as a rigid block (elastic properties are not considered), and the factor of safety of the pillar against vertical downward sliding is given by the ratio of the sum of the shear forces acting on the four sides of the pillar, to the total weight of the pillar, including overburden and free water, if any.

$$\text{Shear FOS} = 2 * (\tau_{xz} * z / x + \tau_{yz} * z / y) / q \quad \text{Eqn. 4.1}$$

where τ_{xz} = shear strength along y dimension

τ_{yz} = shear strength along x dimension

x, y = pillar lateral dimensions

z = pillar thickness

q = total deadload per unit area of pillar, including weight of rock, overburden, and free water.

The shear strengths τ_{xz} and τ_{yz} are determined based on the *Strength Criterion* and *Lateral Stress* parameters input by the user.

After model parameters have been entered, and *Calculate* has been selected, statistical data will be displayed at the bottom of the *plot display box*. A typical output from a RIGID analysis is shown in Figure 4.3.

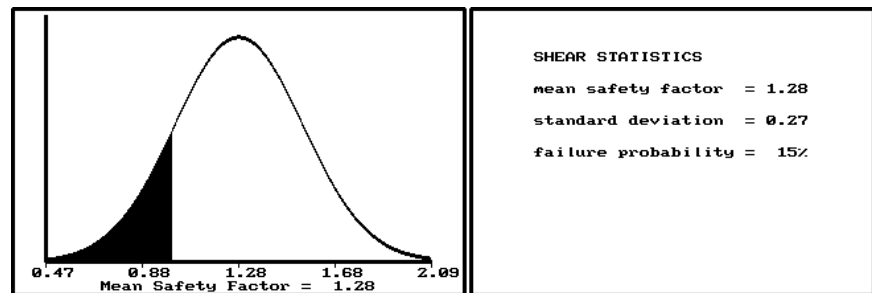


Figure 4.3: Display of SHEAR statistics after a RIGID analysis.

*** NOTE:** The RIGID analysis option in CPILLAR 3.0 performs the same analysis as the original CPILLAR 1.2 program, with the additional functionality of overburden, and new strength and lateral stress options.

Elastic Analysis Failure Modes

Two failure modes are considered in an *ELASTIC* analysis:

SHEAR

and

ELASTIC BUCKLING

Shear

For an *ELASTIC* analysis, the factor of safety of the pillar against vertical downward sliding is given by the ratio of the sum of the shear forces acting on the four sides of the pillar, to the total weight of the pillar, including overburden and free water, as follows:

$$\text{Shear FOS} = 2 * (\tau_{xz} * z1 / x + \tau_{yz} * z2 / y) / q \quad \text{Eqn. 4.2}$$

where τ_{xz} = shear strength along y dimension

τ_{yz} = shear strength along x dimension

x, y = pillar lateral dimensions

$z1, z2$ = (pillar thickness) x (correction factor for bending) in x and y directions (correction factor ≥ 0.5 and ≤ 1.0)

q = total deadload per unit area of pillar, including weight of rock, overburden, and free water.

The form of the equation is identical to that from a *RIGID* analysis, the only difference being that the area on which the shear stresses act is lowered if bending stresses are high. If confining stresses are very low, the shear FOS will be about half that calculated from a *RIGID* analysis. As confining stress is increased, the correction factor for bending approaches 1, so at high confining stress, the shear FOS calculated from either a *RIGID* or *ELASTIC* analysis will be the same.

After *Calculate* has been selected, the results of the *SHEAR* failure mode will be displayed first. A typical output is shown in Figure 4.4.

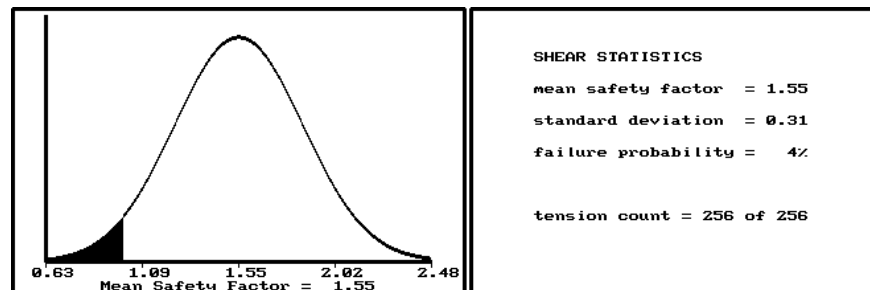


Figure 4.4: Display of *SHEAR* statistics after an *ELASTIC* analysis.

Tension

The '**tension count**' indicates the number of cases where the shear FOS was corrected for bending stresses, as a fraction of the total number of cases analyzed.

If the first number is non-zero, then the **mean SHEAR safety factor** will be between 50 and 100% of that calculated from a RIGID analysis of the same model.

If the first number = zero, then the **mean SHEAR safety factor** will be the same from either a RIGID or an ELASTIC analysis.

The first number will usually be equal to the second number, or zero. In some cases, it may have an intermediate value.

Elastic Buckling

While the SHEAR STATISTICS are being displayed, the user will see the following prompt in the prompt line at the bottom of the screen:

> Hit any key to see ELASTIC BUCKLING probability

Hitting any key will display the elastic buckling statistics, as shown in Figure 4.5.

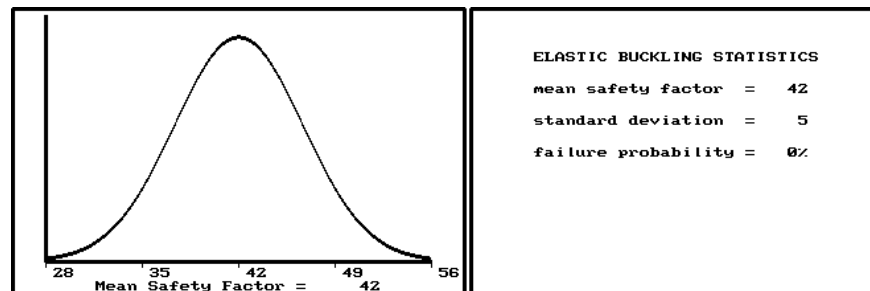


Figure 4.5: Display of ELASTIC BUCKLING statistics after an ELASTIC analysis.

The elastic buckling safety factor is defined as:

$$\text{Euler buckling stress} / \text{Horizontal confining stress}$$

where the Euler buckling stress is equal to:

$$\pi^2 * (\text{rockmass modulus}) * (\text{pillar thickness})^2 / (3 * (\text{span})^2)$$

Elastic buckling FOS will usually be quite high. This is normal.

For this calculation, the roof is treated as a clamped beam, with *span* and *breadth* equal to the *shorter* and *longer* of the x and y dimensions, respectively. The horizontal confining stress = the stress along the breadth of the beam (the longer dimension).

If lateral stresses are very low, the elastic buckling safety factor will be very high, and a VOUSOIR analysis may be more appropriate. Elastic buckling is only an issue when:

- **lateral stresses are high, and/or**
- **span/depth ratio is high, and/or**
- **rockmass modulus is low.**

To apply high lateral stresses to a model, use the **Constant** lateral stress option, which allows the actual horizontal effective stresses to be input.

Due to the inherent uncertainty in applying elastic buckling criteria to rock, a high mean safety factor is recommended (eg. at least > 3), if elastic buckling is an issue. In most situations however, the elastic buckling FOS will be high to very high.

Voussoir Analysis Failure Modes

Three failure modes are considered in a VOUSSOIR analysis:

SHEAR

ARCH SNAP-THRU

and

CRUSHING

Shear

For a VOUSSOIR (no tension) analysis, a rectangular roof is assumed to be divided by cracking into trapezoidal and triangular panels, corresponding to lines of maximum principal tensile stress of an elastic stress analysis. This is illustrated in plan view in the figure below. Such cracking is analogous to the yield lines postulated in the behaviour of reinforced concrete slabs.

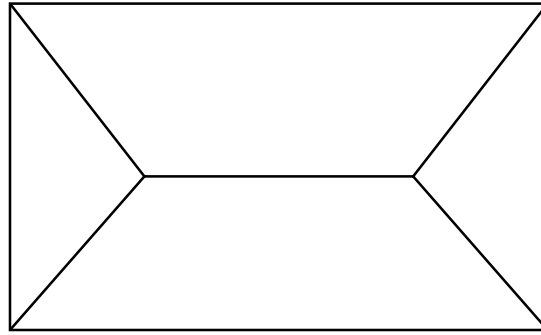


Figure 4.6: Yield lines for a rectangular roof plate (plan view).

For a long excavation ($x \gg y$ or $y \gg x$) this configuration approximates plane strain conditions with a longitudinal crack at midspan. For a square excavation, four equal triangular panels result.

The shear FOS from a VOUSSOIR analysis balances the shear strength of the long excavation dimension against the weight of a trapezoidal panel. This scheme automatically incorporates long or square excavations in the limiting cases of $x = y$ or $x \gg y$ or $y \gg x$. Unlike the RIGID and ELASTIC analyses, the shear strength of the short excavation dimension (and the weight of the smaller 'triangular' panels) does not enter into the shear stability calculation.

Since the lateral compressive stress is solely induced by the arching action of the rock and is not due to external field stresses, low span / depth ratios will result in low shear FOS values, since the rock cannot develop the lateral stress required for a self-supporting arch. This is why span/depth ratios < 3 are not recommended, for a VOUSSOIR analysis.

$$\text{Shear FOS} = \sigma_{\max} * \tan(\phi) * n * b / (\gamma_{\text{EFF}} * a * (b - k)) \quad \text{Eqn. 4.3}$$

where: σ_{\max} = maximum arch compressive stress, minimum value determined by VOUSSOIR analysis iteration procedure.

ϕ = friction angle (Mohr-Coulomb strength criterion)

n = relative thickness (with respect to roof beam thickness) of the compression arch.

b = long dimension of plate (max. of x or y values)

a = short dimension of plate (min. of x or y values)

γ_{EFF} = effective density of roof = (rock contribution + overburden contribution) * $\cos(\text{facedip angle})$ – support pressure

$$= [\gamma_{\text{rock}} * \cos(\text{facedip angle})] + [\gamma_{\text{overburden}} * (\text{overburden thickness/pillar thickness}) * \cos(\text{facedip angle})] - [\text{support pressure} / \text{pillar thickness}]$$

$k = (a / 2) * [(a/b)^2 + 3]^{1/2} - (a/b)$ (a factor accounting for the geometry of the trapezoidal panels illustrated in Figure 4.6)

After performing a VOUSOIR analysis, the SHEAR STATISTICS will be the first failure mode displayed, as shown in Figure 4.7, and the prompt at the bottom of the screen will prompt the user to “Hit any key to see ARCH SNAP-THRU probability”.

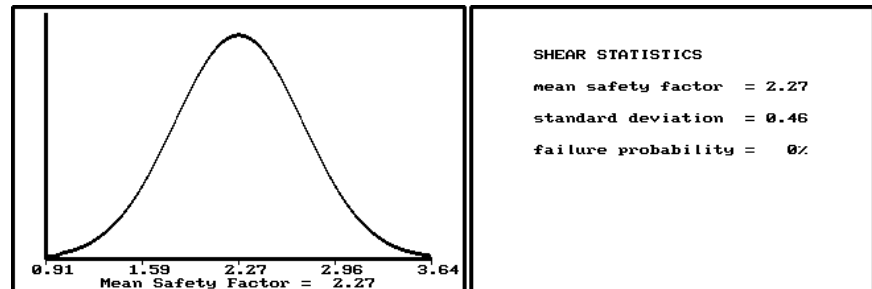


Figure 4.7: Display of SHEAR statistics after a VOUSOIR analysis.

Arch Snap-Thru (Gravity Buckling)

This is the primary failure mode of interest in a VOUSOIR analysis. The essential features of a roof supported by VOUSOIR action are illustrated in Figure 4.8, for a horizontal beam. Deflection has been exaggerated for purposes of illustration.

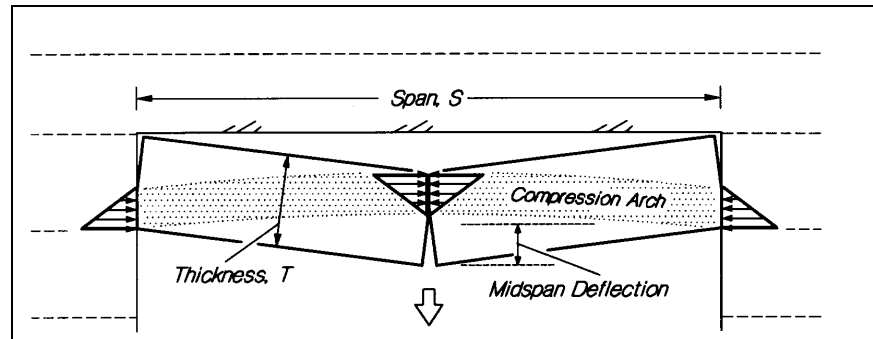


Figure 4.8: Problem geometry for Voussoir stability analysis (Ref.4).

Like elastic buckling, 'arch snap-thru' is highly dependent on geometry (span/depth ratio) and rockmass modulus. However, the driving force for gravity buckling is the self-weight of the rock, whereas the driving force for elastic buckling is the externally applied lateral stress. As such, they are entirely different modes of failure, although both are referred to as buckling failure modes.

When the SHEAR statistics are displayed, the prompt at the bottom of the screen will read:

```
> Hit any key to see ARCH SNAP-THRU probability
```

Figure 4.9 shows the display of ARCH SNAP-THRU statistics which will be displayed after the user hits a key.

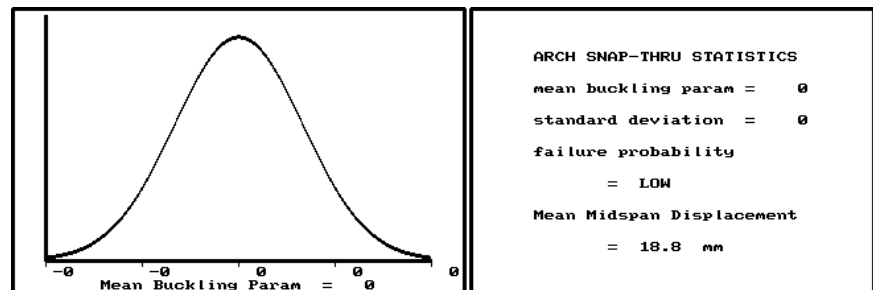


Figure 4.9: Display of ARCH SNAP-THRU statistics after a VOUSOIR analysis.

The '**buckling parameter**' calculated in a VOUSOIR analysis represents the percentage of unstable arch configurations for a given geometry and rock mass modulus, as determined by the VOUSOIR analysis iteration procedure. A buckling parameter = 35% has been determined (Ref. 4) as a limit above which

a roof should be considered unstable. This design limit of 35% happens to correspond to a midspan deflection = 10% of the beam thickness. Therefore arch stability can also be assessed by monitoring the displacement at midspan, relative to the undeflected state. The AVERAGE displacement at midspan (for all statistical combinations of input parameters) is displayed along with the arch snap-thru statistics (see Figure 4.9).

The display of 'failure probability' shown in Figure 4.9 is slightly different than that used for other CPILLAR failure modes. The shaded portion of the distribution curve indicates buckling parameters > 35 (rather than factor of safety values < 1). Also, the failure probability is stated as either: LOW, MEDIUM, HIGH or VERY HIGH, rather than as a precise numerical value, due to the nature of a VOUSSOIR stability analysis. These failure probabilities correspond to mean buckling parameter ranges as indicated in Table 4.1 below.

Failure probability	Mean Buckling Parameter
LOW	0 - 10
MEDIUM !	10 - 25
HIGH !!	25 - 50
VERY HIGH !!!	> 50

Table 4.1: Failure probabilities (Voussoir analysis) corresponding to mean buckling parameter ranges.

NOTE: the design curves of Beer & Meek (Ref. 6) correspond to the CPILLAR solution when the buckling parameter (in CPILLAR) just reaches 100 (ie, 99 to 100). This represents a mathematically critical state which will lead to collapse at the slightest disturbance, and as such is not a conservative design limit. The CPILLAR recommended limit for arch snap-thru stability (buckling parameter < 35) is based on a more conservative but realistic approach to the voussoir concept of roof stability. See Ref. 4 for full details.

Crushing

When the ARCH SNAP-THRU statistics are displayed, the prompt line will read:

> Hit any key to see CRUSHING probability

Hitting any key will display the COMPRESSION statistics, as shown in Figure 4.10.

The iterative procedure used in a VOUSOIR analysis is considered to have converged when a stable minimum value of the induced lateral compressive stress can be determined. This is the stress which holds the arch in place (see Figure 4.8). It arises from considering the moment equilibrium of the driving and resisting force couples acting on the arch.

Triangular stress distributions are assumed to act at the arch abutments and at arch midspan, keeping the arch in place (see Figure 4.8). The most stable configuration for the VOUSOIR arch is that which **minimizes the maximum** stress of these assumed triangular distributions.

If this stress **exceeds the uniaxial compressive strength of the rock**, localized crushing failure is considered to have occurred, and arch snap-thru may follow, even though the primary snap-thru analysis may indicate a stable arch.

$$\text{Crushing FOS} = \frac{\text{uniaxial compressive strength}}{\text{maximum induced lateral compressive stress}} \quad \text{Eqn. 4.4}$$

The crushing FOS will usually be quite high. It will only become a failure mode issue in its own right under certain conditions, when the uniaxial compressive strength is very low. Depending on the **scale** of the rock volume involved, and the presence of **planes of weakness** inclined at some angle from the lateral stress directions, the effective uniaxial compressive strength for the **roof** may be significantly **lower** than the value for **intact rock** specimens. Thus the potential for compressive failure should be based on the minimum value of uniaxial compressive strength to be expected for the transversely isotropic lithological unit (Ref. 5).

For rocks with low compressive strength, the critical displacement at midspan may be less than 10% of the beam thickness (Ref. 4).

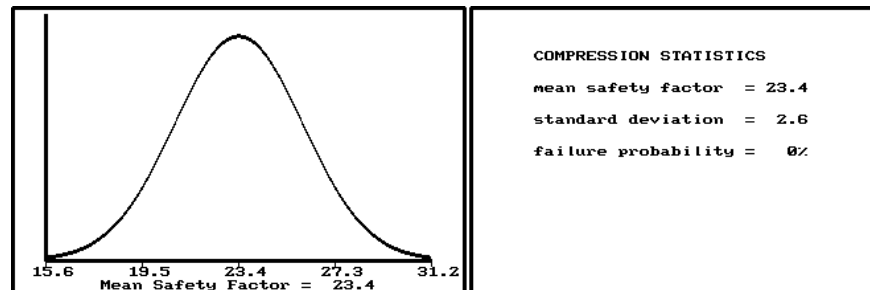


Figure 4.10: Display of COMPRESSION statistics after a VOUSOIR analysis.

Further Information On Voussoir Analysis

The Voussoir analysis used in CPILLAR 3.0 incorporates the latest improvements in the technique. For a full account of this, see Ref. 4.

For more background information on the original and subsequent developments of the Voussoir concept as applied to mine roofs, see *Chapter 8* of Ref. 5, and also Refs. 6 and 7. Reference 7 is the original paper by Evans, where the Voussoir concept as applied to mine roofs was first formulated.

Examples

Example 1 – Rigid Analysis of Square Pillar

If you have not already done so, run the program by typing **CPILLAR** at the DOS prompt.

You will find yourself in the main menu. Highlight the **Rigid** option with the mouse or the keyboard arrow keys, and *select* it by pressing the *left mouse button* or **<Enter>** on the keyboard. Then select *Input Values* from the *Rigid* analysis menu.

```
Select: Rigid
Select: Rigid->Input Values
```

The *Input Values* popup window for a *Rigid* analysis will appear. Input the values shown in Figure 5.1 below. Use the mouse or keyboard arrow keys to highlight and select the appropriate menu options, and type in the values.

RIGID parameters			
Pillar X Dimension	(m)	10	
Pillar Y Dimension	(m)	10	
Pillar Thickness	(m)	4	
Rock Unit Weight	(MN/m3)	0.027	
Overburden Unit Wt	(MN/m3)	0.02	
Water Unit Weight	(MN/m3)	0.01	
Is Pillar Permeable?		No	
Lateral Stress		Gravity	
		mean	std dev
Water Height	(m)	6	0
Overburden Thickness	(m)	1	0.2
Horiz/Vert Kx		0.8	0.1
Horiz/Vert Ky		0.8	0.1
Strength Criterion		Hoek-Brown (RMR)	
		mean	std dev
Rock Mass Rating		35	5
Intact m value		10	2
Intact Strength	(MPa)	60	4
Save [ALT-S]		Abort [ALT-A]	

Figure 5.1: Input Values for RIGID analysis, Example 1.

Features of Example 1 (Input)
<p>Geometry:</p> <p>The above model represents a square pillar (10 x 10 meters) with a thickness of 4 meters, 1 meter of overburden, and 1 meter of free water (6 - (4 + 1)).</p> <p>Lateral Stress:</p> <p><i>Lateral Stress</i> option = Gravity. This is the default setting. Lateral stresses will be calculated based on the Horizontal / Vertical stress ratios (0.8 in both x and y directions).</p> <p>Strength Criterion:</p> <p><i>Strength Criterion</i> = Hoek-Brown (RMR). This is also the default setting. The Hoek-Brown constants m and s will be calculated from the Rock Mass Rating and Intact m values input by the user.</p> <p>Standard deviations have also been entered for most of the parameters, so that a failure probability will be calculated.</p>

When all parameters have been entered, you must Save the data. Select the Save button at the bottom of the Input Values popup window with the left mouse button, or use the keyboard combination <Alt S>. You are now ready to Calculate. Select the Calculate button from the Rigid analysis menu, and the screen will display Figure 5.2.

Select: Rigid->Calculate

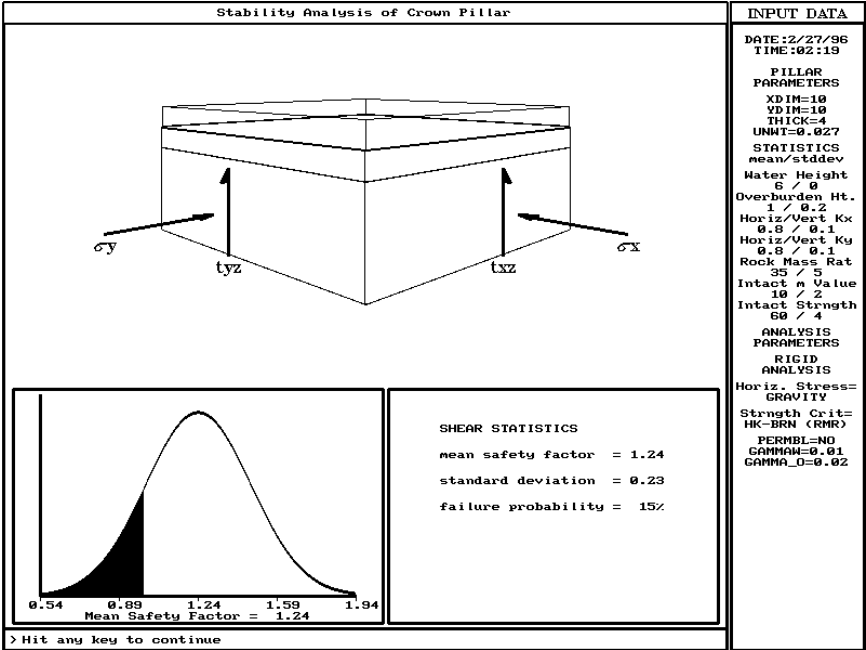


Figure 5.2: Results of Calculating data for Example 1.

Note the failure probability of 15%, indicated by the shaded area under the normal distribution curve of safety factor.

Since the RIGID analysis option has only the one failure mode (SHEAR), hitting any key will clear the analysis results from the screen and return you to the RIGID analysis menu.

Now change some of the input parameters for this example. Select *Input Values* again.

Select: Rigid->Input Values

Toggle the 'Is Pillar Permeable?' option to 'Yes', by selecting it with the *left mouse button*, or hitting <Enter> when the box is highlighted. *Save* the data as before, and *Calculate*.

Select: Rigid->Calculate

You will see the following Warning message appear:

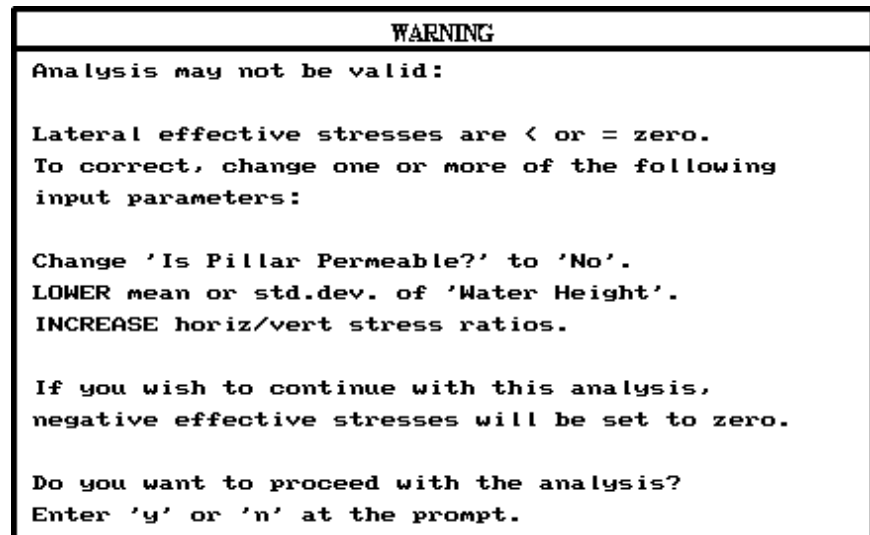


Figure 5.3: Warning message when negative effective stresses are calculated.

Type 'n' at the prompt line, and the analysis will be aborted. (Or type 'y' to see the results of the calculation with negative effective stresses set to zero.)

Since the pillar is now specified as 'permeable', the average lateral effective stress has become negative, due to the effect of the water height. Select *Input Values* once again, **lower** the **water height** to **5 meters**, *Save* the data, and *Calculate*. The SHEAR statistics shown in Figure 5.4 will be displayed.

Note the effect on pillar stability. The **mean safety factor** has *decreased* from 1.24 to 0.78, and the **failure probability** has *increased* from 15% to 84%.

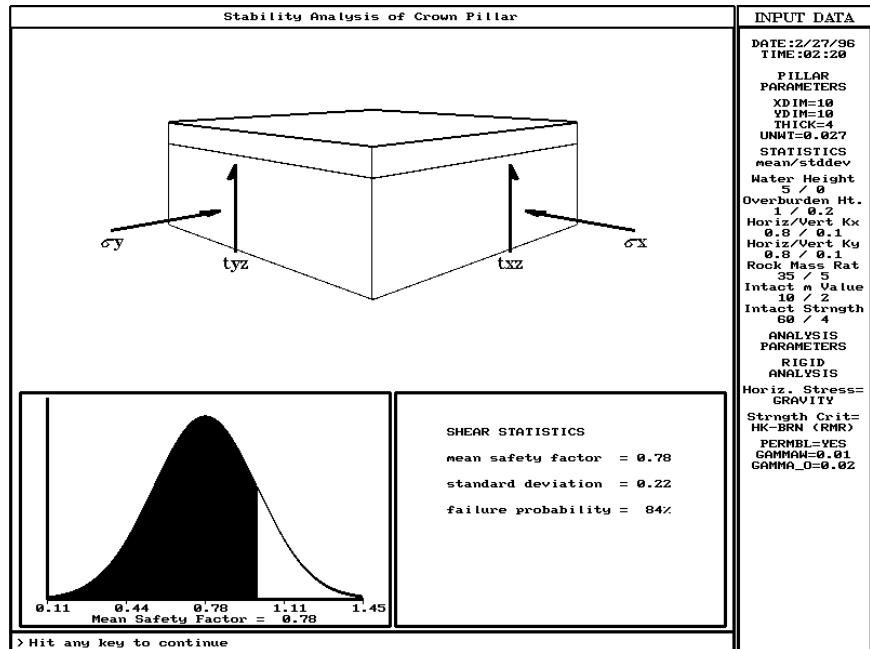


Figure 5.4: Analysis of Example 1, after changing “Is Pillar Permeable?” to ‘Yes’ and lowering water height to 5 meters.

Saving a CPILLAR File

You may wish to save the above example.

Select **RETURN** at the bottom of the RIGID analysis menu, to return to the main menu.

Select: Rigid->RETURN

Now select **Write File** from the main menu, and you will be prompted to enter a file name in the prompt line.

Select: Write File

Type **example1** in the prompt line and press **<Enter>**. *No filename extension is required.*

The data will be stored as file **example1.cpl**. Use any ASCII DOS text editor to view the format of this file.

Example 2 – Elastic Analysis of Roof Beam (Long Excavation)

If you have not already done so, run the program by typing **CPILLAR** at the DOS prompt.

You will find yourself in the main menu. Highlight the *Elastic* option with the mouse or the keyboard arrow keys, and *select* it by pressing the *left mouse button* or **<Enter>** on the keyboard. Then select *Input Values* from the *Elastic* analysis menu.

```
Select: Elastic
Select: Elastic->Input Values
```

The *Input Values* popup window for an *Elastic* analysis will appear. Input the values shown in Figure 5.5 below. Use the mouse or keyboard arrow keys to highlight and select the appropriate menu options, and type in the values. The *Lateral Stress* and *Strength Criterion* options will have to be toggled to *Constant* and *Hoek-Brown*, respectively, from the default values.

ELASTIC parameters			
Pillar X Dimension	(m)	10	
Pillar Y Dimension	(m)	100	
Pillar Thickness	(m)	1	
Rock Unit Weight	(MN/m3)	0.027	
Overburden Unit Wt	(MN/m3)	0.027	
Water Unit Weight	(MN/m3)	0.01	
Is Pillar Permeable?		No	
Lateral Stress		Constant	
		mean	std dev
Water Height	(m)	0	0
Overburden Thickness	(m)	1	0
Horiz. Sigma x'	(MPa)	2	0.5
Horiz. Sigma y'	(MPa)	2	0.5
Strength Criterion		Hoek-Brown	
		mean	std dev
Rockmass m value		0.3	0.05
Rockmass s value		0.0001	0
Intact Strength	(MPa)	50	5
Rock Mass Modulus	(MPa)	5000	1000
Save [ALT-S]		Abort [ALT-A]	

Figure 5.5: Input Values for ELASTIC analysis, Example 2.

When all parameters have been entered, you must Save the data. Select the *Save* button at the bottom of the *Input Values* popup window with the left mouse button, or use the keyboard combination **<Alt S>**. You are now ready to Calculate. Select the *Calculate* button from the *Elastic* analysis menu, and the screen will display Figure 5.6.

Features of Example 2 (Input)
<p>Geometry:</p> <p>The above model represents a roof beam (10 x 100 meters) with a thickness of 1 meter, and 1 meter of overburden having the same density as the beam (ie, an overlying delaminated bed of the same material).</p>
<p>Lateral Stress:</p> <p><i>Lateral Stress</i> option = Constant. Lateral effective stresses of 2 Mpa in both the x and y directions have been entered, with standard deviations of ± 0.5.</p>
<p>Strength Criterion:</p> <p><i>Strength Criterion</i> = Hoeck-Brown. The actual rockmass m and s values have been entered.</p>
<p>Standard deviations have also been entered for some of the parameters, so that a failure probability will be calculated.</p>

Select: Elastic->Calculate

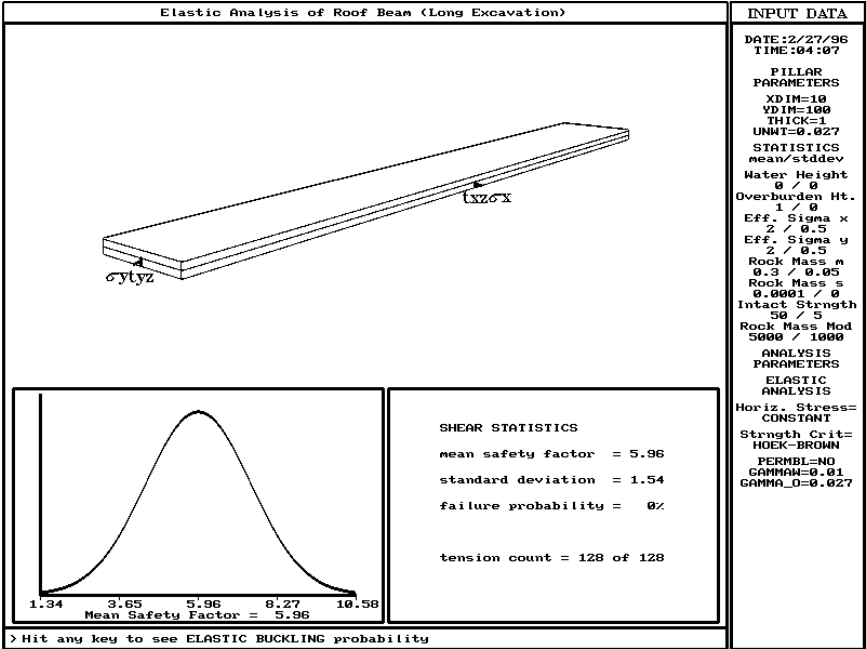


Figure 5.6: SHEAR statistics after *Calculating* data for Example 2.

The prompt line will indicate “Hit any key to see ELASTIC BUCKLING probability”. Hit any key, and the SHEAR statistics will be replaced by the ELASTIC BUCKLING statistics shown in Figure 5.7.

Note the 'tension count' in the display of SHEAR statistics. This indicates the number of cases where the shear strength was lowered due to bending induced tensile stresses. If the first number is zero, then a RIGID analysis will give the same SHEAR factor of safety. In general, the SHEAR factor of safety from an ELASTIC analysis will be between 50 and 100% of that determined from a RIGID analysis, depending on the magnitude of the calculated bending stresses, and the lateral stresses.

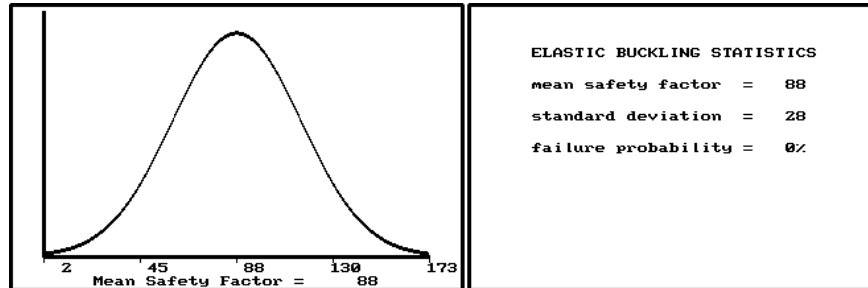


Figure 5.7: ELASTIC BUCKLING statistics after *Calculating* data for Example 2.

Note that the ELASTIC BUCKLING safety factor is high. This is to be expected. Elastic buckling will only be an issue if (1) lateral stresses are high, and/or (2) span/depth ratio is high, and/or (3) rockmass modulus is low.

Now select *Input Values* again, and enter a beam thickness of **5 meters**. *Save* the revised data after making the change. Now select *Calculate*, and the following Warning message will be displayed:

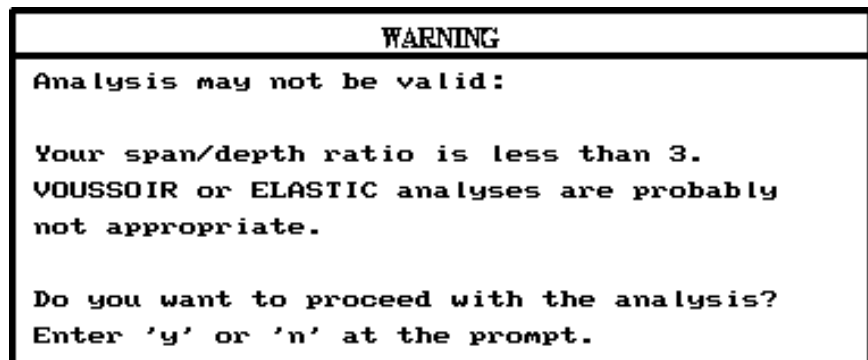


Figure 5.8: Warning message for low span/depth ratio.

Both the elastic buckling and bending stress calculations will not be valid with such a low span/depth ratio (2 : 1 has been entered). Span/depth ratios should be at least about 4 or 5 for ELASTIC or VOUSOIR analyses to be valid. However, the user has the option of going ahead with the calculation, but you have been warned!

Type an 'n' and press <Enter> to abort the analysis.

Example 3 – Voussoir Analysis of Rectangular Roof Plate

If you have not already done so, run the program by typing **CPILLAR** at the DOS prompt.

You will find yourself in the main menu. Highlight the ***Voussoir*** option with the mouse or the keyboard arrow keys, and *select* it by pressing the *left mouse button* or **<Enter>** on the keyboard. Then select *Input Values* from the *Voussoir* analysis menu.

```
Select: Voussoir
Select: Voussoir->Input Values
```

The *Input Values* popup window for a *Voussoir* analysis will appear. Input the values shown in Figure 5.9 below. Use the mouse or keyboard arrow keys to highlight and select the appropriate menu options, and type in the values. The *Strength Criterion* option will have to be toggled to *Mohr-Coulomb*, so that the friction angle can be entered.

VOUSSOIR parameters			
Pillar X Dimension	(m)	30	
Pillar Y Dimension	(m)	20	
Pillar Thickness	(m)	2.5	
Rock Unit Weight	(MN/m3)	0.03	
Overburden Unit Wt	(MN/m3)	0	
Face Dip	(deg°)	0	
		mean	std dev
Overburden Thickness	(m)	0	0
Support Pressure	(MPa)	0	0
Strength Criterion		Mohr-Coulomb	
		mean	std dev
Cohesion		0	0
Friction angle	(deg°)	30	5
Intact Strength	(MPa)	45	5
Rock Mass Modulus	(MPa)	3500	500
Poisson Ratio		0.25	0.05
Save [ALT-S]		Abort [ALT-A]	

Figure 5.9: Input Values for VOUSSOIR analysis, Example 3.

When all parameters have been entered, you must Save the data. Select the Save button at the bottom of the Input Values popup window with the left mouse button, or use the keyboard combination <Alt S>. You are now ready to Calculate. Select the Calculate button from the Voussoir analysis menu, and the screen will display Figure 5.10.

Features of Example 3 (Input)
<p>Geometry:</p> <p>The above model represents a rectangular roof plate (30 x 20 meters) with a thickness of 2.5 meters.</p> <p>Lateral Stress:</p> <p>External lateral stress is not an option for a VOUSSOIR analysis. Lateral stress exists, but it is induced by the ‘arching’ action of the rock, it is not an input parameter.</p> <p>Strength Criterion:</p> <p><i>Strength Criterion</i> = Mohr-Coulomb. Cohesion is automatically set to zero for a VOUSSOIR analysis when using the Mohr-Coulomb strength criterion. Only a friction angle is entered.</p> <p>Standard deviations have also been entered for some of the parameters, so that a failure probability will be calculated.</p>

Select: Voussoir->Calculate

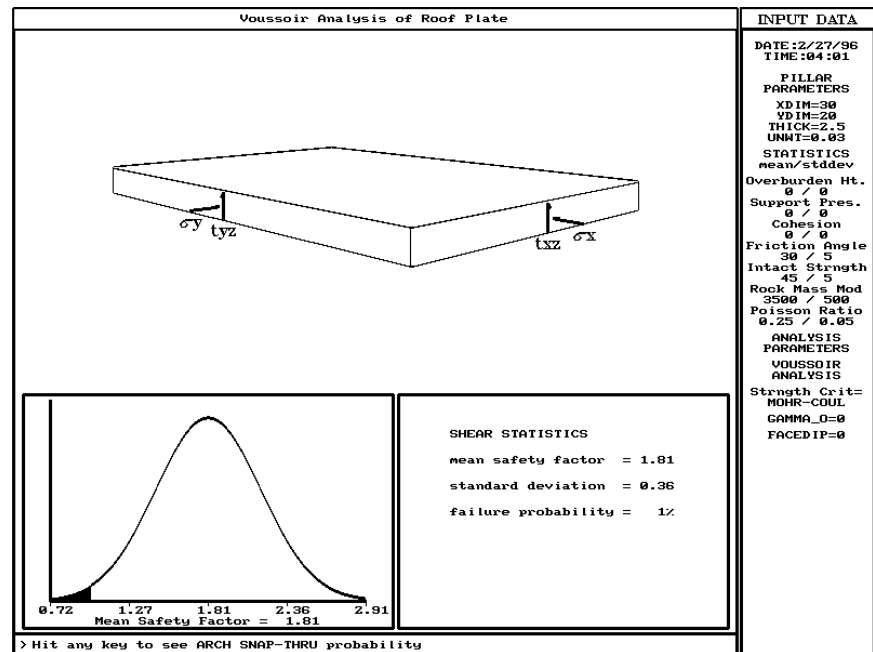


Figure 5.10: SHEAR statistics after *Calculating* data for Example 3.

The prompt line will indicate “Hit any key to see ARCH SNAP-THRU probability”. Hit any key, and the SHEAR statistics will be replaced by the ARCH SNAP-THRU statistics. See Figure 5.11.

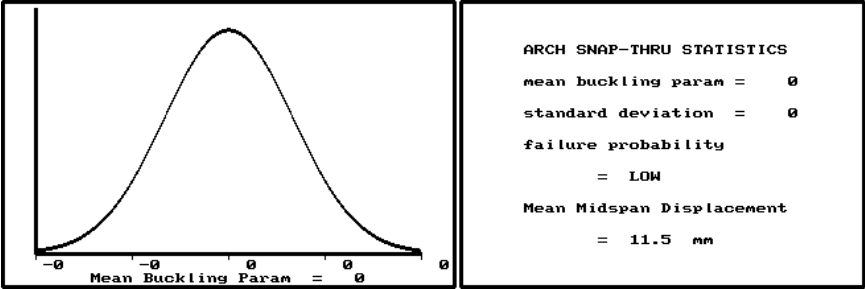


Figure 5.11: ARCH SNAP-THRU statistics (Example 3).

The prompt line will then indicate “Hit any key to see CRUSHING probability”. Hit any key, and the ARCH SNAP-THRU statistics will be replaced by the COMPRESSION statistics. See Figure 5.12.

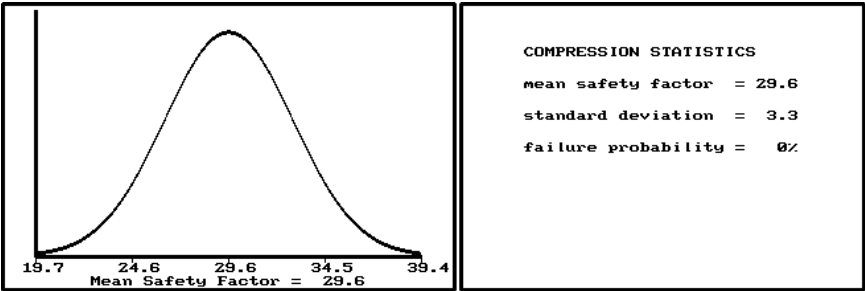
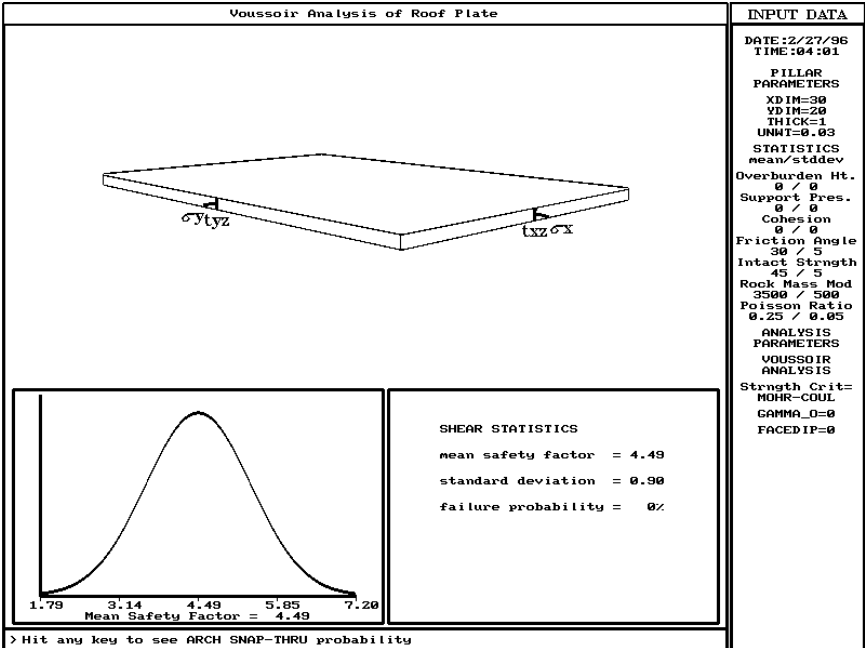


Figure 5.12: COMPRESSION statistics (Example 3).

Now let’s gradually collapse our arch by decreasing the plate thickness. Select *Input Values*, and enter a pillar thickness of **1.0 meters**. Save the revised data, and select *Calculate*. The resulting SHEAR, ARCH SNAP-THRU and COMPRESSION statistics are shown below.



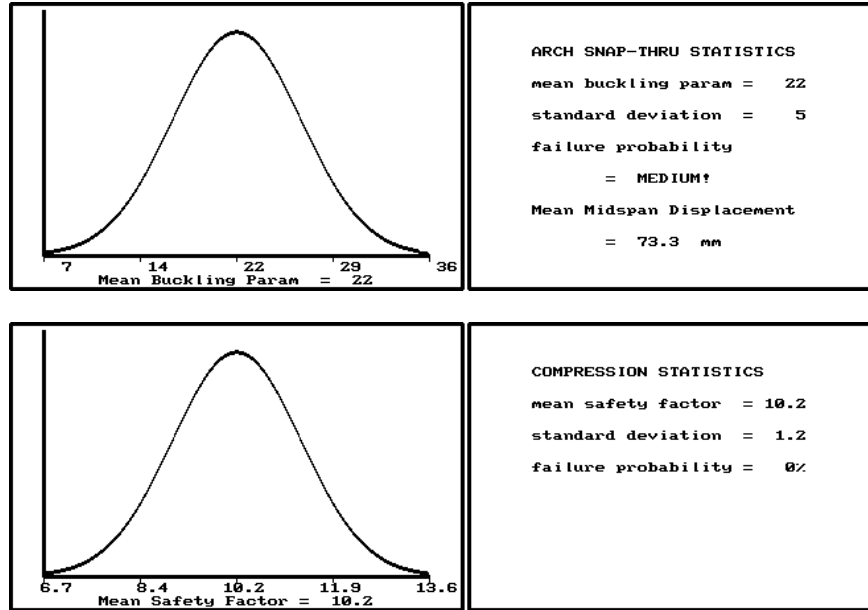
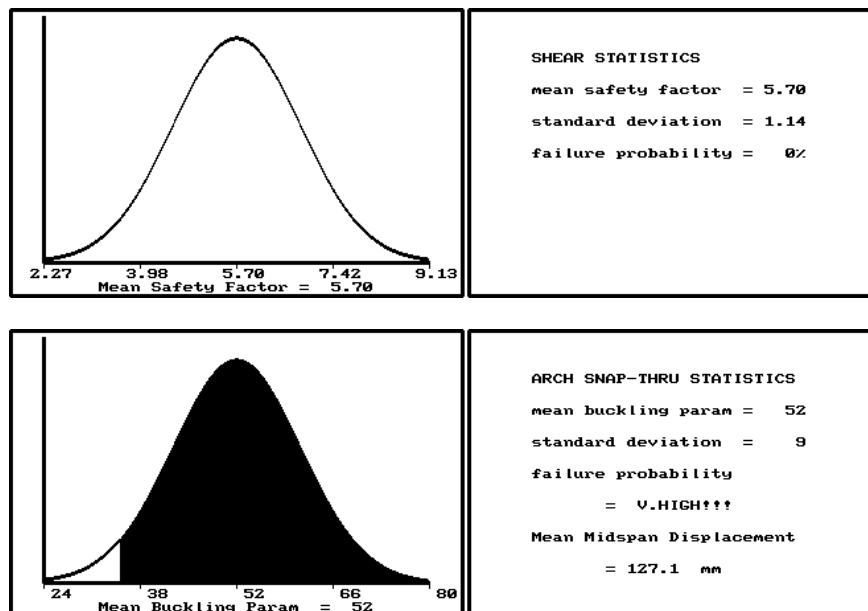


Figure 5.13 a,b and c: Example 3 analysis, plate thickness reduced to 1 m.

Note that the SHEAR factor of safety *increases*, while the SNAP-THRU and COMPRESSION factors of safety *decrease*. Note also the increase in the arch Midspan Displacement, from 11.5 mm to 73.3 mm.

Select *Input Values* again and enter a pillar thickness of **0.8 meters**. Save the new data and *Calculate*. The results are shown below.

- ↓ Plate thickness
- ↓ Snap-thru stability
- ↓ Crushing FOS
- ↑ Shear FOS



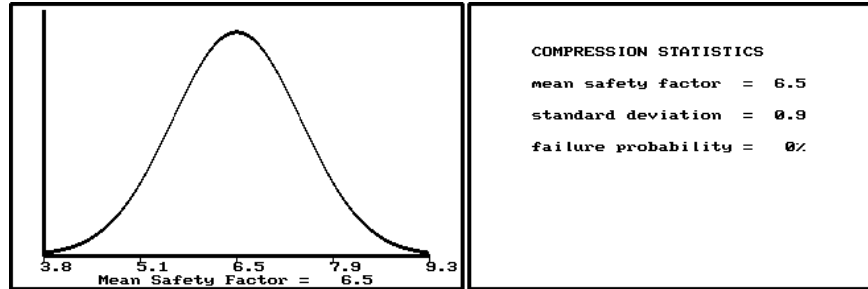


Figure 5.14 a,b and c: Example 3, plate thickness reduced to **0.8 meters**.

Again, SHEAR factor of safety *increases*, while SNAP-THRU and COMPRESSION stability *decreases*. Arch midspan displacement is now **127 mm**. Recall that when the midspan displacement reaches about 10% of the plate or beam thickness, arch collapse is imminent.

NOTE that this point of critical stability – when the buckling parameter in CPILLAR just reaches 100 – corresponds to the Beer & Meek solution (Ref.6), for a given problem geometry.

Finally, reduce the plate thickness to 0.6 meters, and *Calculate*. The arch is completely unstable, and failure probability is 100%. (NOTE that this point of critical stability – when the buckling parameter in CPILLAR just reaches 100 – corresponds to the Beer & Meek solution (Ref.6), for a given problem geometry).

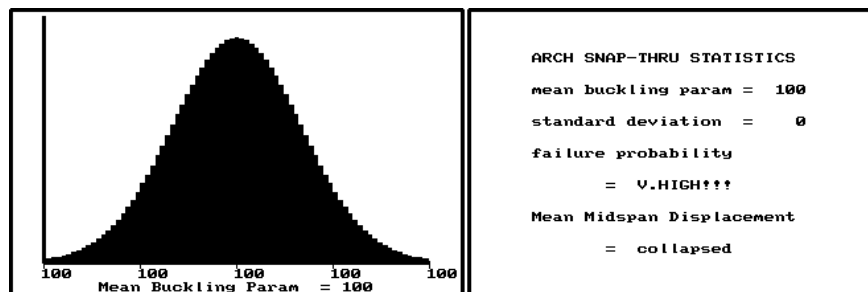


Figure 5.15: Arch has collapsed due to decrease in plate thickness.

It is left to the user to experiment with other variables. For instance, enter a mean **support pressure = .01 Mpa**, and re-enter the original plate thickness of 2.5 meters. *Calculate* the results. Gradually increase the support pressure in increments of .01 Mpa. You will find that the midspan displacement will decrease towards zero, the COMPRESSION safety factor will increase to 100.0 (an arbitrary number indicating a high value), and the SHEAR factor of safety remains virtually unchanged.

This last result may seem unusual, however it is an outcome of the VOUSOIR analysis technique, and the fact that the shear strength is based only on the Mohr-Coulomb friction angle. In fact, it is generally true of a VOUSOIR analysis, that **the SHEAR factor of safety will not change** as the deadload is increased or decreased, all other parameters being constant, whether the change in effective deadload is due to a change in rock density, addition of overburden, specifying a dip angle, or addition of support pressure.

This will not necessarily be true if the user is working with the Hoek-Brown *Strength Criterion*.

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