ANALYSIS OF MINE ROOF SUPPORT

Analysis of Mine Roof Support

Version 1.0

Sunday, May 7, 2023

Table of Contents

Part I

1 AMRS

Overview

The File Menu

The Edit Menu

Parametric Graphs

The Utilities Menu

The Help Menu

References

About AMRS

Help File Updated: Sunday, May 7, 2023.

1.1 Overview

During the past 15 years, roof fall rates have fallen dramatically in US coal mines, particularly in regions where the roof is weakest. The remarkable reduction in the number of roof falls has been accomplished with more effective roof support systems. The purpose of this paper is to present a design methodology that builds on and quantifies the basic roof support concepts that have been successful in the US. The methodology starts by defining three modes of roof support, based on the roof strength relative to the stress level:

1. Strong roof, where roof bolts mainly provide skin control,
2. Moderate strength roof, which can be supported by roof bolts alone, and
3. Weak roof, which needs secondary support like cable bolts.

Next, a large data base of roof fall histories at a number of mines is used to define the approximate boundaries of these three regimes, based on the Coal Mine Roof Rating and the depth of cover. Finally, guidelines are presented for site-specific design of support systems within each regime. The computer package Analysis of Roof Support Systems (AMRS) implements the design methodology.

Part II

2   The File Menu

Description:

Use the File menu option to access various file management operations such as:

Creating New Files

Opening Existing Files

Saving Files

Saving Files under Different Names (Save As)

Setting up the Printer

Printing Files

Print Preview

Browsing Text Files

Exiting the Program

2.1   Creating New Files

Description:

Use the New option to erase the existing dataset (if any) from memory and create a new (blank) dataset. All related entries are set to their initial values.

Notes:

- The program will prompt you whether to save the current file to disk.

2.2   Opening Existing Files

Description:

Use the open option to load a file (dataset) from the disk into program memory.

To use Open:

- Select the Open option from the File menu. The program displays a listing of the available files in the current data directory.
- Optionally, select a different drive or directory using the mouse or the cursor control keys.
- Select or enter a filename.

Notes:

- If the file extension is omitted, the default extension will be appended.
- If the current dataset is not saved, the program will prompt whether to save changes or not before discarding the current dataset.

2.3   Saving Files

Description:

Use the Save option to save an existing file (dataset) to the drive or directory from which it was originally loaded. Any changes that were made since the last time the file was saved will be saved on the disk. The filename stays the same and the file remains in memory.

To use Save:

Select the Save option from the File menu.

Notes:

- If the file has never been saved using the Save As option, choosing Save automatically displays the Save As dialogue box, which prompts for a filename before saving it.

2.4   Saving Files under Different Names (Save As)

Description:

Use the Save As option to save a file and give it a new name.

To use Save As:

- Select the Save As option from the File menu. The program displays a listing of the available files in the current data directory.
- Optionally, select a different drive or directory.
- Select or enter a file name.

Notes:

- If the file exists, the program will prompt whether to overwrite the existing file.
- Saving an unnamed file will default to *Save As.*

2.5 Setting Up the Printer

Description:

Use this option to select the Printer to use for printing output and graphics. This printer becomes the Windows default printer.

To use this option:

Select the Printer from the drop down list and click on OK.

2.6 Printing Files

Description:

Use the Print option to print the current dataset (file) from program memory to the default windows printer. The default printer may be set using the Setting Up the Printer menu option.

Notes:

- The file is send directly to the printer, without preview. Use the Print Preview option to preview the file and then send it to the printer.

2.7 Print Preview

Description:

The user may navigate through the Print Preview Window by using the vertical scroll bar.

The text in the window can be send directly to the printer, or it can be copied to the Windows clipboard for use in other applications.

Notes:

- This operation does not send any control characters to the printer. All output is ASCII text. The text prints in "Courier" or "Courier New" font in size 9. If these fonts are not available to the printer, then printed text will appear in the default printer font.
- Each printed page is formatted with preset margins as follows:
  - ✓ left margin = 1 inch
  - ✓ top margin = 1 inch
  - ✓ bottom margin = 1 inch
  - ✓ right margin = variable

2.8   Browsing Text Files

Description:

Use the browse option to view a text (ASCII) file in a specified directory. No editing is allowed during browsing.

Use the pattern field to specify a file pattern (i.e. *.txt). The file window will be reset to conform to the specified pattern. The default pattern is *.ARB. More than one patterns can be applied using ";" as delimiter (e.g. *.txt;*.dxf).

Use the *Set Font* command button to specify the type and size of font for the displayed text. These settings are saved in the AMRS.INI file.

Use the cursor control keys to move within the browse window.

2.9   Exiting the Program

Description:

Use the Exit option when ready to exit this program and return to the original environment. The program will prompt you to save the current file to disk, if not already saved.

Part

III

3 The Input Menu

Description:

Use the Input menu option to access various parameter input/edit forms such as:

Project Description

Project Parameters

3.1 Project Description

Description:

This is an arbitrary 300 character description of the model being generated. It is a recommended to make this a fairly detailed description of the specifics of the input file. This text may be a single line of characters or may contain "carriage return characters".

The user can set the type of units that will be used in the current project. The program is designed to use two different sets of units:
- ft and lbs
- m and kN

The user can also select the type of steel strength that will be used in the current project. The program is designed to use either yield strength (grade) that characterizes roof bolts used in the US or ultimate tensile strength (UTS) that characterizes roof bolts used in Australia.

3.2 Project Parameters

AMRS uses four basic input parameters to describe the roof rock quality, stress level, roof span, and roof support density.

Rock quality is described by the Coal Mine Roof Rating (CMRR). The CMRR was developed in 1994 to quantify geologic descriptions of coal measure rocks into a single strength rating (Mark and Molinda, 2005). The Coal Mine Roof Rating (CMRR) measures the structural competence of the roof on a 0-100 scale, with higher values meaning stronger roof. It can be determined either through underground observation or from exploratory drill core. Based on more than 25 years of experience, conservative estimates of the CMRR for typical roof types in different US coalfields have been prepared (Table 1). These values apply to single rock units. Where the roof consists of several units, they are combined to obtain the composite CMRR of the roof structure. A computer program that aids in calculating the CMRR from underground or core data can be obtained at https://www.cdc.gov/niosh/mining/works/coversheet1812.html.

Table 1. Estimates of CMRR for typical roof rock in different US coalfields

Rock Type	Coalfield			
	Northern Appalachian	Central Appalachian	Midwest	Western US
Claystone	35	40	35	35-40
Shale	40	45	38-40	45
Siltstone	45	50	45	50-55
Sandstone	55	55-65	45	55-65
Limestone	55		50-65	

Stress level includes both the vertical load due to weight of the overburden and the horizontal stress that originates in plate tectonics. Actual in situ stresses are rarely measured in US coal mines, but the available data clearly indicates that the horizontal stress increases with depth, though the gradient may vary from coalfield to coalfield (Mark and Gadde, 2008). The cover depth (H (ft)) is therefore used as the input for AMRS. The user should enter the typical depth of cover for an area, not the maximum beneath a ridge or the minimum beneath a stream valley. In fact, the stresses may actually be concentrated beneath stream valleys.

Roof span is a third fundamental parameter that affects the stability of underground structures (Mark and Barczak, 2000). The entry width is self-explanatory. For four-way intersections, ARMS requires the sum-of-the-diagonals (SumD). These are normally measured underground, or the maximum allowed by the Roof Control Plan may be used. If no measurements are available, the following are typical values (source: Mark, 2000):

Entry Width (ft)	SumD (ft)
16	60
18	64
20	66

If the actual SumD seems too small for the entered We (defined as smaller than 4 feet plus ($(2*We^2)^{0.5}$)), then the following warning is printed: "Intersection diagonals and entry width may not match".

Roof support density captures the load-bearing capacity of the roof support system. A number of input parameters are needed to define it, depending on the type of roof support system that is being analyzed (Figure 11).

Primary Support / Roof Bolts
Lb = Length of the bolts (ft)

Nb = Number of bolts per row,
Gr = Bolt grade (nominal yield strength, ksi) (may be specified through drop down menu with standard values or manually),
Db = Bolt diameter (inches) (may be specified through drop down menu with standard values or manually),
Sb = Spacing between rows of bolts (ft)

The Stability Factor is a final input parameter for analysis of primary support. An AMRS SF of 1.0 is currently considered appropriately conservative. Figure 10 shows that the AMRS suggested PSUP values with SF=1.0 are approximately equivalent to the 2001 ARBS suggested values with an SF=1.5.

The user can select a standard roof bolt setup with respect to bolt diameter and grade (Table 2), or they can select any combination diameter and grade combination.

Table 2. Standard roof bolt diameters and grades available in the US

US Roof Bolts	Diameter (in)	Grade (ksi)
#5 smooth - grade 55	0.625	55
#5 rebar - grade 60	0.625	60
#5 smooth - grade 75	0.625	75
#5 special rebar - grade 75	0.677	75
#6 rebar - grade 40	0.75	40
#6 rebar - grade 60	0.75	60
#6 smooth - grade 75	0.75	75
#7 special rebar - grade 75	0.804	75
#7 rebar - grade 40	0.875	40
#7 rebar - grade 60	0.875	60

Secondary Supports
The rock load height is the assumed thickness of the broken roof that needs to be carried by the total support. Often the observed height of past roof falls can be used (see Figure 9).

The roof fall angles, relative to vertical, will also significantly impact the volume of immediate roof. For example, a roof fall with vertical shear planes on each side will result in loads 1.5 to 2.0 times larger than a similar fall with a 45-degree fall angle. In general, the weaker the roof the steeper the roof fall angle. Typical roof fall angles are shown in Table 3 (Mark and Stephan, 2019).

Table 3. Typical observed roof fall angles.

Roof Geology	Fall Angle (degrees)
Competent siltstone (CMRR>50)	45
Strong shale (CMRR= 40-45)	30
Weak shale/claystone (CMRR=35)	26

The density of most coal measure sedimentary rock is about 162 lbs per cubic foot.

Secondary Support / Cable Bolts
Lcb = Length of the cable bolts (ft),
Dcb = Diameter of the cable bolts (inches) (may be specified through a drop down menu),
Cb = Capacity of the cable bolts (tons) (may be specified through a drop down menu with standard values or manually,
Ncb = Number of bolts per row (entries) or per intersection,
Scb = Spacing between rows of cable bolts (entries only) (ft).

Note1: The two common cable bolt sizes used in the U.S. coal mining industry are 0.6- and 0.7-inch-diameter, with ultimate tensile capacities of 26.4-and 35.7-tons, respectively.
Note2: When using metric units the program will only allow the user to specify the cable bolt capacity (MPa) without reference to the diameter. The user can select a value from a list or specify a value manually.

Secondary Support / Truss Bolts
Ltb = Length of angled member (ft),
Phi = Truss angle (degrees),
Ctb = Truss capacity (tons),
Stb =Truss spacing (entries only) (ft).

Note 1: Truss angle is typically 45 degrees.
Note 2: Truss capacity is typically the breaking strength (or anchorage capacity) of one of the angled members.

Secondary Support / Roof Bolts
Lsb = Length of the bolts (ft)
Nsb = Number of bolts per row,
Gsr = Bolt grade (nominal yield strength, ksi) (may be specified through a drop down menu with standard values or manually),
Dsb = Bolt diameter (inches) (may be specified through a drop down menu with standard values or manually),
Ssb = Spacing between rows of bolts (entries only) (ft).

Secondary Support / Standing Support
Support Type (drop down menu available),
Css = Capacity per standing support (tons)
Nss = Number of standing supports per row (entries) or per intersection,
Sss = Spacing between rows of standing supports (entries only) (ft).

To calculate the load-bearing capacity of a standing support system, AMRS requires the capacity of an individual support. Users may input their own value, but AMRS also provides a menu of the capacities of some of the most common standing supports. Because the load carried by a standing support depends the amount of convergence it

is subjected to, the values in the menu are the support capacities at two inches of convergence. Table 4 below also provides the maximum capacity of each support.

Table 4. Support capacities for different standing support types

Support type	Peak capacity between 0-2 inches deflection (tons)	Peak capacity (tons)
4-point Hardwood Crib (8" x 8" timbers, 5' height)	90	158
4-point Hardwood Crib (8" x 8" timbers, 7' height)	74	140
4-point Hardwood Crib (6" x 6" timbers, 5' height)	51	89
4-point Hardwood Crib (6" x 6" timbers, 7' height)	42	79
9-point Hardwood Crib (6" x 6" timbers, 7' height)	94	178
Link-N-Lock (24")	92	150
Link-N-Lock (36")	132	198
Wood Post (6")	22	22
Wood Post (8")	66	66
55-ton ACS Jack	55	55
100-ton ACS Jack	100	100
Propsetter (10")	72	90
Pumpable Crib (24")	135	135
Pumpable Crib (30")	202	202
CAN (24")	95	118
Concrete Crib (24" x 24")	525	525

The data listed in Table 4 was obtained through https://www.cdc.gov/niosh, the National Institute for Occupational Safety and Health's Support Technology Optimization Program (STOP). The STOP software is used to assist in making engineering decisions regarding the selection and placement strategy of various standing roof support technologies. Additional support types and combinations can be evaluated through a free download of the STOP software at:
https://www.cdc.gov/niosh/mining/works/coversheet1819.html

AMRS compares the rock load height to the secondary support length to check whether and adequate anchor length is available. Cable bolts should anchor in 3-4 feet of stable ground above a potential roof fall, while roof bolts need at least 1 foot of anchorage. A warning prints in the output if the length of the anchor may be inadequate.

Note: When ultimate strength is used, it is internally converted to yield strength to perform PSUP calculations. The ultimate strength is used for RDI and PRSUP calculations.

3.3   Calculations

The suggested sum of the diagonals (SumDg) (Figure 8) is determined using the equation:

SumDg (ft)= 46.1 + 0.38 (CMRR)
SumDg (m)= 14.1 + 0.12 (CMRR)

If the actual sum of the diagonals SumD exceeds the suggested sum of the diagonals, SumDg, a warning is given by the program, but AMRS may still be used.

The suggested Bolt Length, Lbg, is determined using the equation:

Lbg (ft) = (SumD / 13) * log10(H) * ((100-CMRR)/100)$^{1.5}$
Lbg (m) = (SumD / 4) *[(0.51+ log10(H))/3.25] * [(((100-CMRR)/100)$^{1.5}$)/3.25]

where:
SumD = the actual sum of the diagonals (ft or m).

If the actual bolt length is shorter than the suggested length, a warning is given by the program. If the bolts are more than 2 ft longer than the suggested value, a warning is also given. A design with very long bolts that have low capacity or are on a wide spacing may not be successful even if its PSUP appears adequate.

The Actual PSUP (Primary Support Rating index) is determined using the equation below:

PSUP = (Lb * Nb * C) / (Sb * We) (Standard units)
PSUP = (Lb * Nb * C) / (14.5 * Sb * We) (Metric units)

where:
Lb = the length of the bolt (ft or m),
Nb = the number of bolts per row,
Sb = the spacing between rows of bolts (ft or m),
We = the entry width (ft or m), and
C = the yield capacity of the bolt (kips or kN).

The bolt capacity (C) is obtained by multiplying the grade of the steel (Gr) (in ksi or MPa) by the cross-section area of the bolt (in^2 or mm^2). The bolt capacity needs to be greater or equal to 8.45 tons to meet ASTM requirements.

PSUP is a rough measure of the amount of steel installed in the roof. Its dimensions are kips/ft or kN/m, but it should be considered an index, rather than a physical parameter. It does not consider the type of bolt (that is, fully-grouted vs point anchor, tensioned vs non-tensioned, etc.), because it is difficult to show that one bolt type is superior to another. Table 5 provides PSUP values calculated for typical primary roof bolting patterns in US coal mines.

Table 5. PSUP values calculated for typical primary roof bolting patterns in US coal mines.

Bolt Length (ft)	Bolt Yield Capacity (tons)	Entry Width (ft)	Bolts per Row	Row Spacing (ft)	PSUP
4	8.8	20	4	5	2.9
4	8.8	20	4	4	3.5
5	13.3	20	4	4	6.6
6	13.3	18	4	4	8.8
8	13.3	18	4	4	11.8
8	16.6	18	4	3.5	16.8

The support capacity of a single truss (Cst) is calculated as:

Cst = 2 * (Ctb * sin (Phi))

where:
Ctb = truss capacity, and
Phi = truss angle.

Figure 13 illustrates the calculation.

AMRS also reports the Reinforcement Density Index (RDI) and PRSUP, two parameters that are used extensively for roof support design in Australia (Thomas, 2010; Molinda et al., 2000; Colwell and Frith, 2009). The RDI and PRSUP values are calculated using the following equations:

RDI = 14.5 * (Lb * Nb * CU) / (Sb * We) -- (Standard units)
RDI = (Lb * Nb * CU) / (Sb *We)   (Metric units)

PRSUP = (Lb * Nb * CU) / (Sb * We) -- (Standard units)
PRSUP = (Lb * Nb * CU) / (14.5 * Sb * We) -- (Metric units)

Where CU = the ultimate (tensile) capacity of the bolt (kips or kN)

If the user enters the bolt grade (Gr) in Standard units, AMRS converts it to the ultimate tensile strength of the bolt steel (UTS (ksi)) using the following logic (based on the minimum values provided in Table 3 of ASTM F432):

UTS (ksi) = (GR * 0.9) + 35

AMRS uses the following equation to convert the ultimate strength of the bolt steel (CU) to the yield strength (Gr):

GR (ksi) = (UTS - 35) / 0.9

For cable bolts, the Secondary RDI (SRDI) is given by the equations:

SRDI = 14.5 ((Lcb-1) * Ncb * CUcb) / (Scb * We) -- (Standard units)
SRDI = ((Lcb-0.33) * Ncb * CUcb) / (Scb * We) -- (Metric units)

where 0.33 m or 1 ft is subtracted from the length of the cable bolt for the "tail."

The secondary PRSUP for cable bolts is given by the equations:

PRSUPcb = (Lb * Ncb * CUcb) / (Scb * We) -- (Standard units)
PRSUPcb = (Lb * Ncb * CUcb) / (14.5 * Scb * We) -- (Metric units)

The secondary PRSUP uses the **primary roof bolt length**, rather than the length of the cable bolts, in the calculation. In addition,
Ncb = the number of cable bolts per row,
Scb = the spacing between rows of cable bolts (ft or m),
CUcb = the yield capacity of the cable bolt (kips or kN).

The dimensions of RDI, SRDI and PRSUP are kN/(1000 m)).

3.4   Results Window

Description:

The text is organized in pages. By default, the user views the first output page, which is usually the second page. The first page is reserved for printing the input data.

The user may navigate through the text of a single page using the vertical scroll bar and the arrow keys. No editing is allowed.

Text can be selected (block select) and copied to the clipboard using Ctrl-C. Use Ctrl-A to select all text in a page.

In addition, use the command buttons below for additional output navigation and/or printing operations:

Previous Page: Display the previous page of output (if any)

Next Page: Display the previous page of output (if any)

View Plot: Display a plot of the geometry of the mining plan with options to display dimensions or pillar properties

Print Page: Print current page to any Windows printer.

Print All: Print all pages to any Windows printer.

Copy Page: Copy current page to the clipboard.

Copy All: Copy all pages to the clipboard (pages separated by carriage return characters).

Generate Graphs: Generate a number of parametric graphs based on the input data. For more details see Parametric Graphs.

Part IV

4   Parametric Graphs

Description:

The user can create 10 types of parametric graphs:
- Suggested PSUP vs CMRR
- Suggested PSUP vs Depth of Cover
- Suggested PSUP vs Stability Factor
- Suggested PSUP vs Intersection Span
- Rock Load vs Rock Height (Entries)
- Rock Load vs Entry Width (Entries)
- Rock Load vs Roof Fall Angle (Entries)
- Rock Load vs Rock Height (Intersections)
- Rock Load vs Sum of Diagonals (Intersections)
- Rock Load vs Roof Fall Angle (Intersections)

All graphs are created by by varying the independent parameter around the value set in the input form.

The figure below shows how suggested PSUP decreases with increasing CMRR.

Analysis of Mine Roof Support
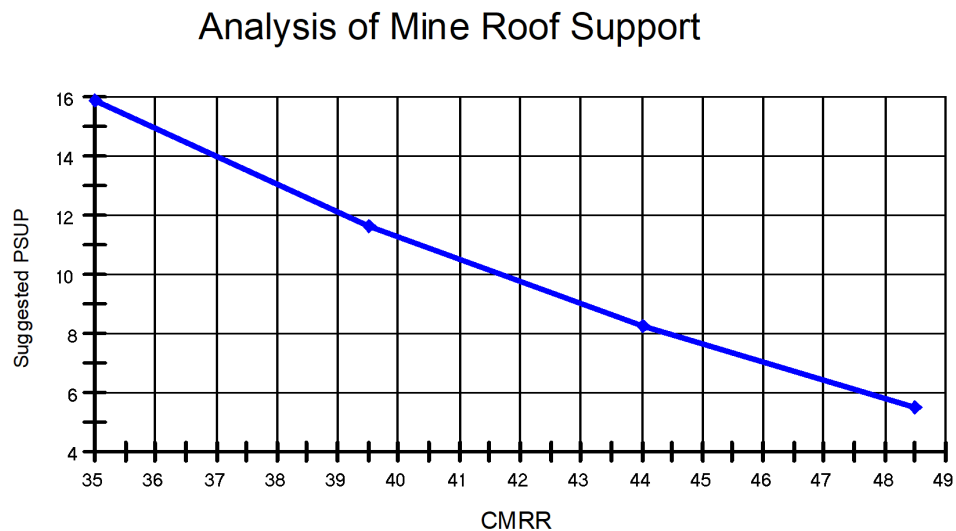
The figure below shows how the suggested PSUP increases with increasing depth of cover.

Analysis of Mine Roof Support
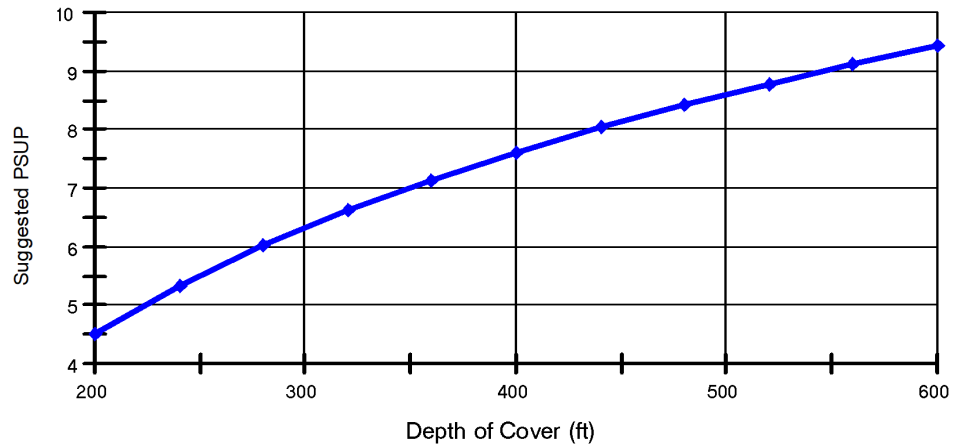
The figure below shows how the suggested PSUP increases with increasing stability factor.

Analysis of Mine Roof Support
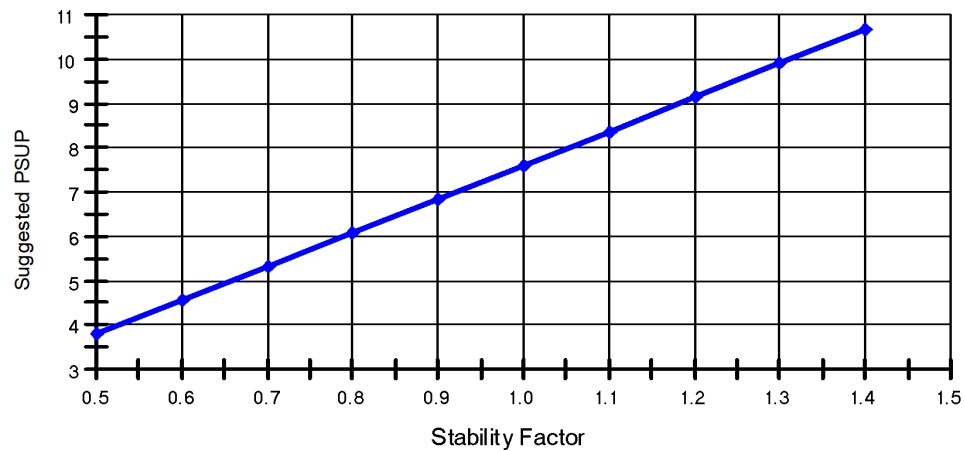
The figure below shows how the suggested PSUP increases with increasing sum of diagonals.

Analysis of Mine Roof Support
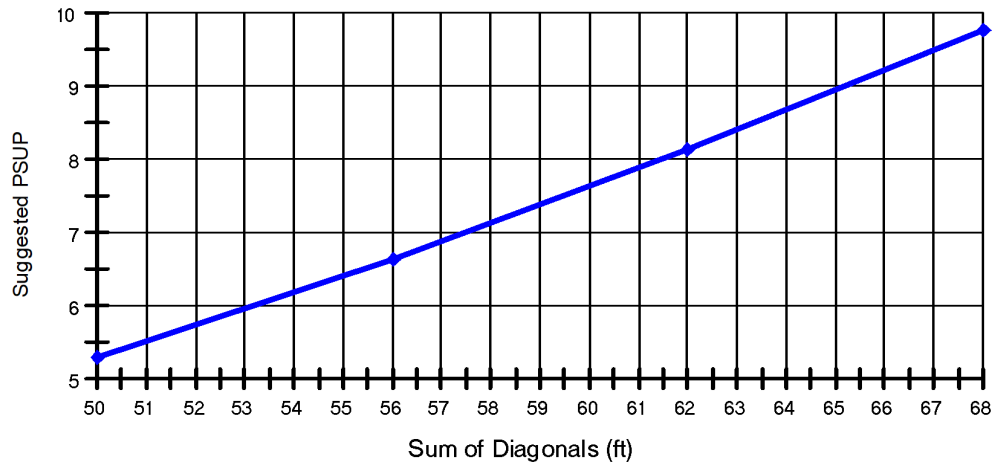
The figure below shows how the Rock Load along Entries (tons/ft) increases with increasing Rock Load Height for the given Entry Width and Roof Fall Angle. The maximum Rock Load Height value in the graph corresponds to the maximum possible Rock Load Height for the given Entry Width and Roof Fall Angle.

Analysis of Mine Roof Support
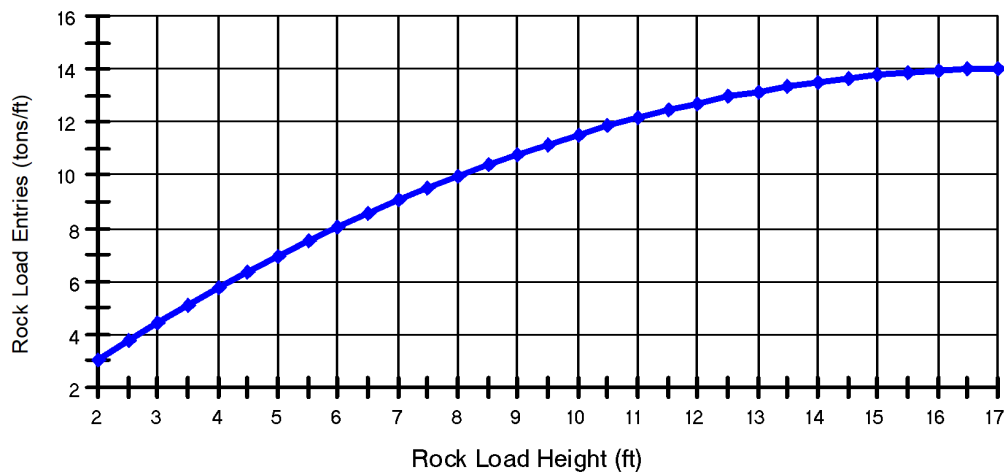
The figure below shows how the Rock Load along Entries (tons/ft) increases with increasing Entry Width for the given Rock Load Height and Roof Fall Angle.

Analysis of Mine Roof Support
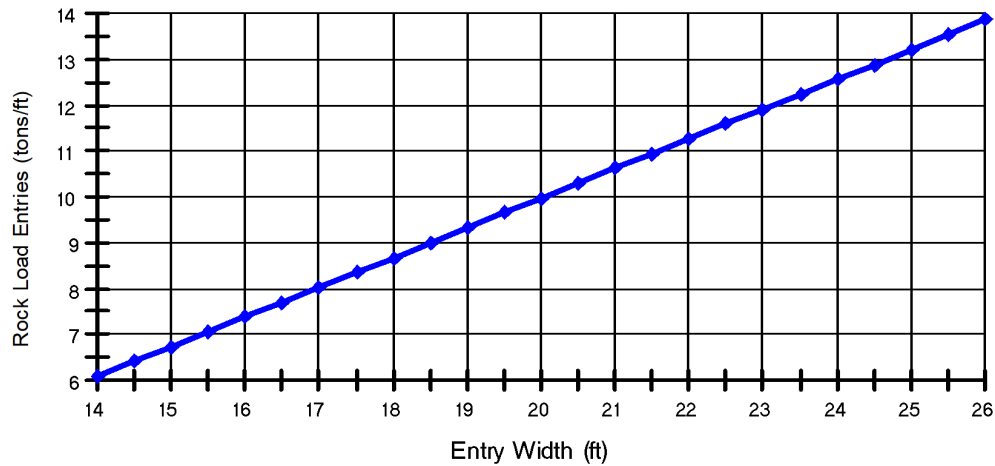
The figure below shows how the Rock Load along Entries (tons/ft) decreases with decreasing Roof Fall Angle for the given Rock Load Height.

Analysis of Mine Roof Support
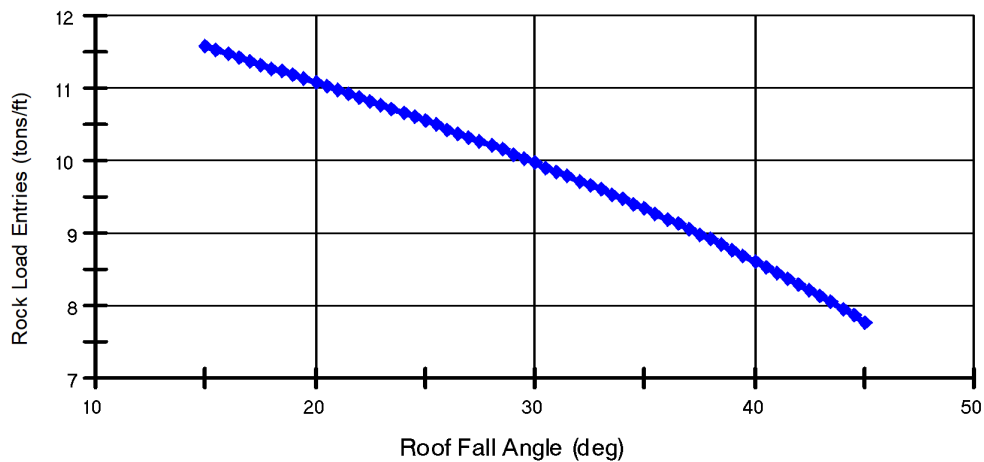
The figure below shows how the Rock Load along Intersections (tons) increases with increasing Rock Load Height for the given Sum of Diagonals and a Roof Fall Angle which is the minimum angle between the Roof Fall Angle for Entries and Crosscuts.

Analysis of Mine Roof Support

The figure below shows how the Rock Load along Intersections (tons) increases with increasing Sum of Diagonals for the given Rock Load Height and a Roof Fall Angle which is the minimum angle between the Roof Fall Angle for Entries and Crosscuts.

Analysis of Mine Roof Support
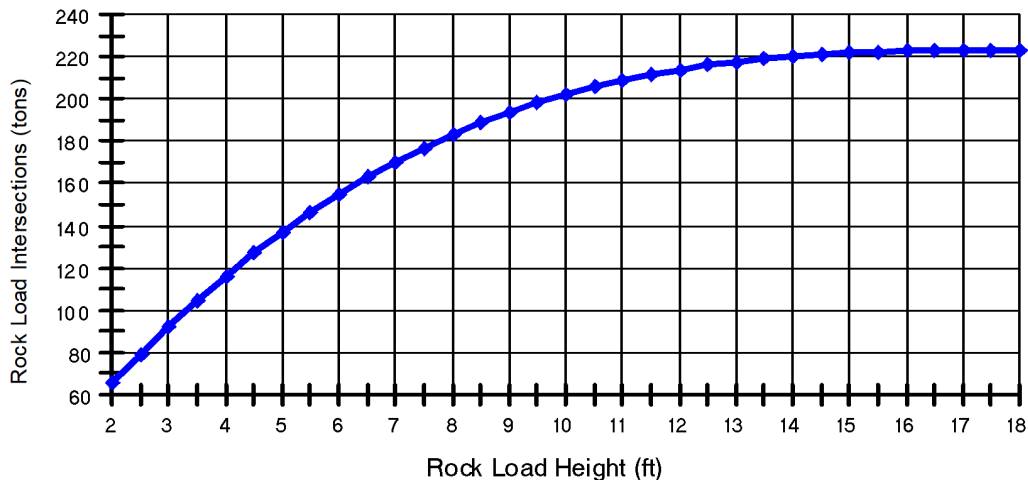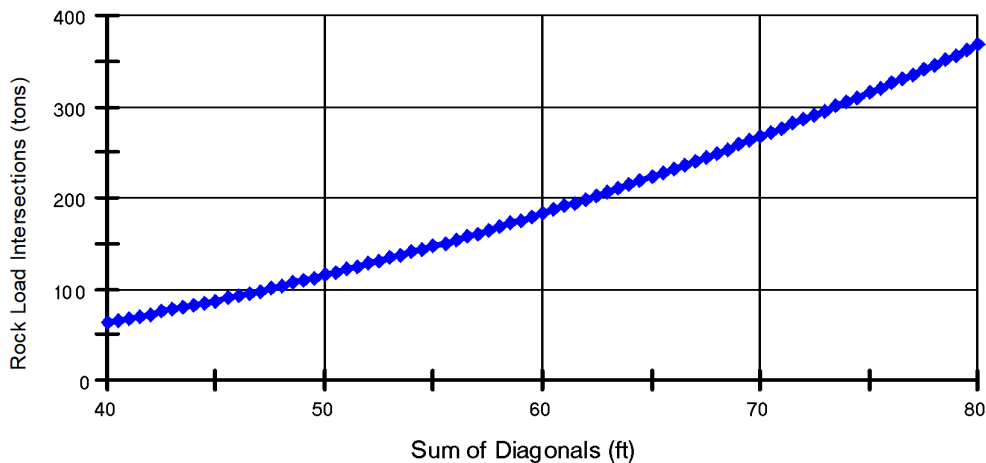
The figure below shows how the Rock Load along Intersections (tons) decreases with increasing Sum of Diagonals for the given Rock Load Height and a Roof Fall Angle which is the minimum angle between the Roof Fall Angle for Entries and Crosscuts.

Analysis of Mine Roof Support
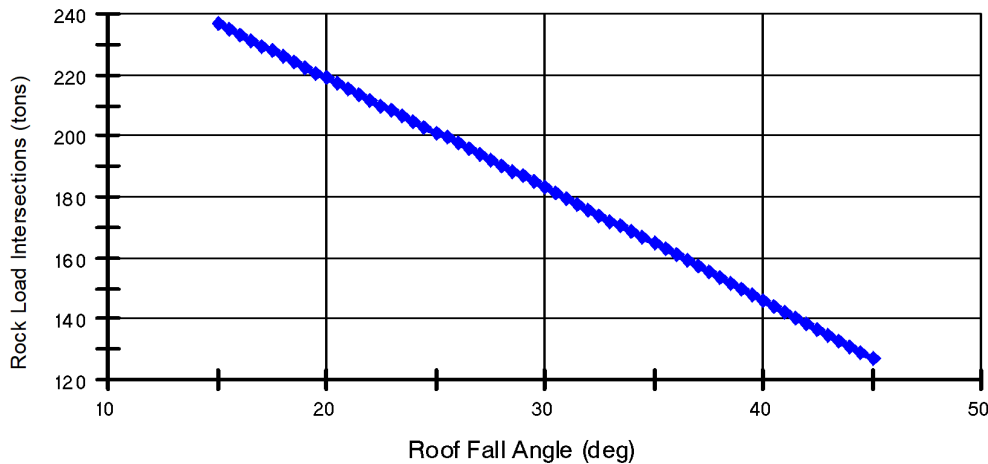
Note: In parametric graphs that show how rock load varies, when the user input value of the rock load height exceeds the maximum height (based on the span and the roof fall angle), then the maximum possible height is used.

See also: Graph Options and The Graph Form

4.1   Graph Options

Description:

The user can set the basic graph formatting parameters as detailed below:

Graph Title
The graph title is a text string placed over the graph.

Graph X-axis Title
The x-axis titles selection includes 10 text fields, one for each type of parametric graph that can be specified. These 10 fields correspond to the x-axis titles of the following graph types:
- Suggested PSUP vs CMRR
- Suggested PSUP vs Depth of Cover
- Suggested PSUP vs Stability Factor
- Suggested PSUP vs Intersection Span
- Rock Load vs Rock Height (Entries)

- Rock Load vs Entry Width (Entries)
- Rock Load vs Roof Fall Angle (Entries)
- Rock Load vs Rock Height (Intersections)
- Rock Load vs Sum of Diagonals (Intersections)
- Rock Load vs Roof Fall Angle (Intersections)

These text strings are placed below the x-axis of each graph.

Graph Y-axis Title

The y-axis titles selection includes three text fields, one for each group of parametric graphs that can be specified. These three fields correspond to the following y-axis titles:

- Suggested PSUP
- Rock Load (Entries)
- Rock Load (Intersections)

Grid Style

Four grid styles are available: Horizontal lines, vertical lines, horizontal and vertical lines, no grid lines.

Graph Style

Three graph styles are available: lines, symbols, lines and symbols.

Curve Legend

This option enables or disables the legend box in the graph.

Symbol Size

With this scroll box the user can set the size of the symbols used by the graph object. The scroll box is enabled only for a graph type of "symbols" or "lines and symbols".

Default Formatting Parameter Options

There are two options for the basic formatting parameters:

- To set the formatting parameters (i.e. graph title, x-axis title, etc.) every time the graph options form is invoked.
- To set the formatting parameters to the ones used in the previous graphing session. These values are saved in the AMRS.INI file.

See Also: The Graph Form

4.2   The Graph Form

Description:

This form is used to display a graph generated by the calling program. The menu options available are:

File-Print
This option prints the graph to the default printer.

File-Export to Excel
This option exports the data to an Excel spreadsheet.

File-Exit
This option closes the graph form. On some occasions, the option to either keep the graph or to clear the graph is available.

Edit-Copy
This option copies the graph box to the clipboard for use in other applications.

Edit-Clear Graph
This option clears the graph box from the current graph.

Options-Basic Options
This option loads the graph options form which includes basic graph formatting options.

Options-Point ID
When this feature is enabled, the graph object will display the coordinates of each point graphed on the graph form. Just click on any point of any curve on the graph and the coordinates of this point will be displayed in the appropriate boxes. This feature is active when a graph is displayed.

Notes:

- Graphics support is provided by Graphics Server 4.53, which is an independent graph control not included in the Microsoft Visual Basic 6.0 package.

See also: Graph Options, Parametric Graphs

Part V
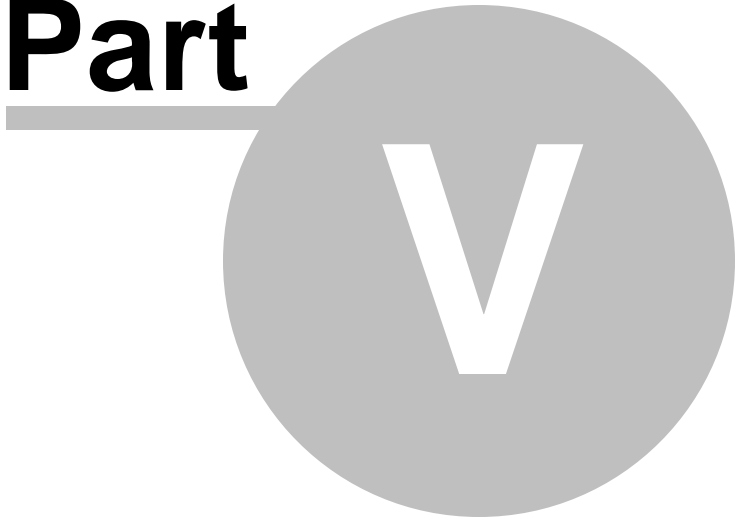
5 The Utilities Menu

Settings

Options

Unit Conversions

File Conversion

Clear History Window
This option clears the history (activity) window.

Close/Restore History Window
This option closes or restores the history (activity) window according to the current window status.

Copy History Window
This option copies the contents of the history window to the clipboard. You can then paste them to any text handling program for further processing.

5.1 Settings

Description:

This form is used to define a number of default parameters and settings for the AMRS program:

Default Units:
This setting controls the default units for a new or blank project file by configuring the Units field in the Project Description form. Upon entering and accepting project input parameters, the default setting in the Project Description form cannot be changed. This setting is saved in the AMRS.INI file.

Default File Extension for Input Files:
This setting is the default 3-letter extension used in the Open and Save dialog boxes in the File Menu. This setting is saved in the AMRS.INI file.

Data Path:
This setting is the default path used in the Open and Save dialog boxes in the File Menu. This setting is saved in the AMRS.INI file.

Show Disclaimer:
This parameter controls whether the disclaimer message will be displayed when loading the AMRS program. This setting is saved in the AMRS.INI file.

Maximize Main Menu Window:

This parameter controls whether the main menu window will be maximized when loading the AMRS program. This setting is saved in the AMRS.INI file.

Keep Recent Filelist:

This parameter controls whether the program will keep the four (4) recently accessed data files (opened or saved) as menu items in the File Menu. This setting is saved in the AMRS.INI file.

Reminder of Annual Updates:

This parameter controls whether the program will display a warning that a year has elapsed since the last update of the program. The update date is internally stored and it is not related to the install date. Annual updates ensure that any bugs that have been discovered are fixed regularly. This setting is saved in the AMRS.INI file.

Display Command History Window:

This parameter controls whether the program will display recently executed commands (and their resulting actions). This setting is saved in the AMRS.INI file.

Maximum Characters in Command History Window:

This parameter sets the maximum number of characters displayed in the command history window, before it is cleared. This setting is enabled only if the Display Command History Window option is enabled. This setting is saved in the AMRS.INI file.

History Font:

This button sets the type and size of font used in the command history window. This setting is enabled only if the Display Command History Window option is enabled. This setting is saved in the AMRS.INI file.

Enable Toolbar:

This settings controls whether the program will display a toolbar under the main menu options or not. The toolbar is not editable. This setting is saved in the AMRS.INI file.

Short Names in Filelist:

This parameter controls whether the program will display the filenames in the recently accessed list in a short or long format (i.e. including the whole path). This setting is saved in the AMRS.INI file.

Load Last Input File:

When this setting is enabled, the program will automatically load the most recently saved datafile (i.e. the top in the recently accessed files). This setting is saved in the AMRS.INI file.

Copy Example Files:

When this setting is enabled, the program will automatically copy all example files from the "Program Files (x86)" directory to the user home directory (i.e. MyDocuments/MyGroundControl). This procedure runs upon every program invocation

unless disabled. The modified files will not be overridden, but missing files will be replaced. This setting is saved in the AMRS.INI file.

External ASCII Viewer:

This option allows the user to specify the external ASCII viewer/editor that will be used when displaying ASCII data. The default setting in this option is to use the Notepad editor. This setting is saved in the AMRS.INI file.

5.1.1   AMRS.INI

Description:

This file is automatically created by the AMRS program the first time it is executed. It should reside in the default document directory for this program, i.e. in the MyGroundControl subdirectory of the (My) Documents directory in the computer where the program is installed (\Documents\MyGroundControl\). Note that in a network environment the Documents directory may reside on a different hard drive. The INI file contains entries such as the ones shown below (the sequence and parameter values may be different in the actual file):

```
[Settings]
DefaultUnits=0
DisplayActionWin=1
MaxDisplaySize=300
KeepFileNames=1
ShowDisclaim=0
DataPath=C:\Users\User\Documents\MyGroundControl\AMRS\
FileExtension=ARS

[FileMenu]
MaxLastFiles=4
LastFile1=C:\Users\User\Documents\MyGroundControl\AMRS\S1.ARS
LastFile2=C:\Users\User\Documents\MyGroundControl\AMRS\S2.ARS
LastFile3=C:\Users\User\Documents\MyGroundControl\AMRS\S3.ARS
LastFile4=C:\Users\User\Documents\MyGroundControl\AMRS\S4.ARS

[TextBrowse]
BrowseFontName=Courier New
BrowseFontSize=10
BrowseFontBold=0
BrowseFontItalic=0
```

Note:

- If this file is deleted, it will be automatically reconstructed the next time the program is executed but the various settings will default to their original values.

5.2   Options

Description:

This form is used to define a number of default parameters and settings for the AMRS program:

Edit / Print Options

Load the Input Form on File Open

If this option is enabled, the input project parameters form will be automatically loaded in the following situations:

- File - New is selected.
- File - Open is selected and a file is loaded.
- An existing file is loaded from the recent file list.

View Project File in Child Window

If this option is enabled, then the View button in the AMRS parameter entry form will launch a separate view window with a sketch of the mine plan. The image in this window can be copied or printed.

Print Module Version Information

If this option is enabled, then whenever the input data are printed, a three-line header is prepended with the program version, filename, etc.

Create a File Association

Use this option to create an association between the program executable and the extension of the project files. Thus, double-clicking on a project file, will invoke the AMRS program.

Default Parameters (English and Metric)

In this tab default values for a number of parameters are set. The program suggests default values, but the user may customize the default value menu. Each time a new project is initialized, the respective fields are loaded with the default values. These include:

Geology
- Coal Mine Roof Rating (CMRR)
- Depth of Cover (m and ft)
- Unit Weight (lbs/ft^3 and kN/m^3)

Support
- Stability Factor
- Actual Bolt Length (ft and m)
- Bolt Diameter (in and cm)
- Bolt Grade (bolt yielding strength) (ksi and MPa)
- Ultimate Bolt Strength (ksi and MPa)
- Number of Bolts per Row

- Row Spacing (ft and m)

Mining Factors

- Actual Intersection Sum of Diagonals (ft and m)
- Entry Width (ft and m)

Bolt Grade Definitions

The user can enter values for bolt grades in sequence. The default set is 40, 55, 60, 75, 90 and 100 ksi. Default metric strength values (in MPa) are provided as well.

Bolt UTS Definitions

The user can enter values for bolt Ultimate Tensile Strength in sequence. The default set is 40, 55, 60, 75, 90, and 100 ksi. Default metric strength values (in MPa) are provided as well.

Bolt Diameter Definitions

The user can enter values for bolt diameters in sequence. The default set is 0.625, 0.688, 0.75, 0.804 and 0.875 in (which corresponds to 5/8" rebar, 3/4" rebar, 7/8" rebar, 3/4" Jbar, 7/8" Jbar). Default metric diameter values (in mm) are provided as well.

Cable Bolt Capacity and Diameter Definitions

The user can enter values of cable bolt capacity and diameters. The default set is 0.6" at 26.4 tons and 0.7" at 35.7 tons. These values are correlated so that the first capacity value corresponds to the first diameter value and so on. Default metric values (in mm and kN) are provided as well.

Standing Support Type and Capacity

The user can enter/edit values for standing support types and their respective capacity in tons and kN.

The figure below shows the default parameters in English (Standard) units. The user can edit the values and also edit the individual lists for bolt grade and bolt diameter as well as the grid for cable bolt capacity and diameter. These values will populate the respective drop down combo boxes under Project Input Parameters. The user can restore default values by clicking *Reset Default.*
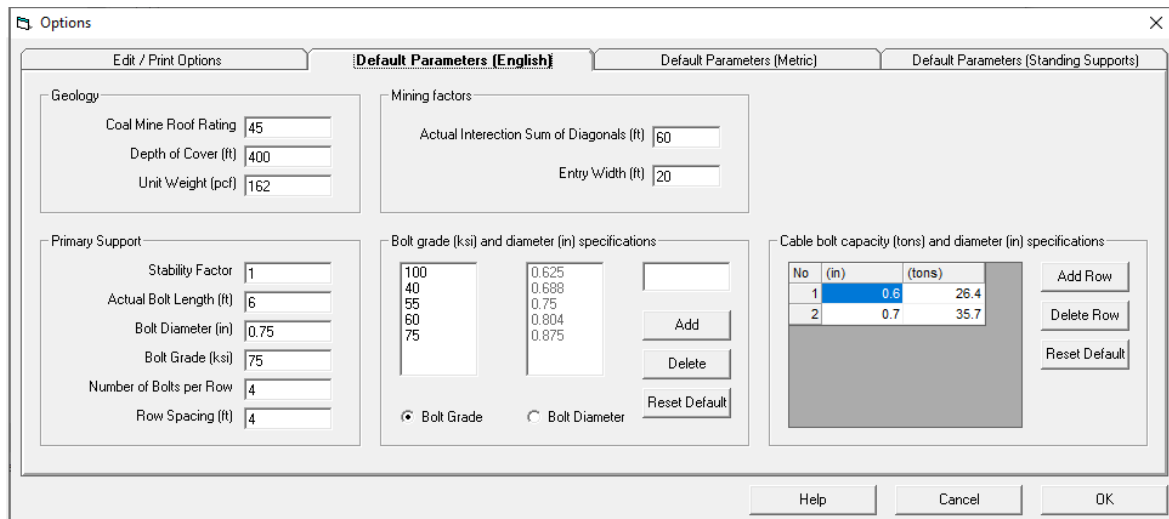
The figure below shows the default parameters in Metric units. The user can edit the values and also edit the individual lists for bolt grade and bolt diameter as well as the grid for cable bolt capacity and diameter. These values will populate the respective drop down combo boxes under Project Input Parameters. The user can restore default values by clicking *Reset Default.*

The figure below shows the default standing support types and their capacity in tons and kN. The user can edit the list and add and/or delete support definitions. The user can restore default values by clicking *Reset Default.*

5.3   Unit Conversions

Description:

This utility can be used to convert between English and metric units for 4 types of units:

Pressure

Conversion between psi (pounds per square inch), Pa (Pascals) and MPa (MegaPascals) is supported.

Length

Conversion between feet, inches, meters and centimeters is supported.

Stress (Pressure) Gradient

Conversion between psi/ft (psi per foot), psi/in (psi per inch), MPa/m (MegaPascal per meter) and Pa/m (Pascal per meter) is supported.

Load Gradient

Conversion between lbs/ft (pounds per foot), lbs/in (pounds per inch), kN/m (kiloNewton per meter) and MN/m (MegaNewton per meter) is supported.

Notes:

- 1 Pa = 1 Newton per square meter
- 1 psi = 1 pound per square inch

5.4   File Conversion

Description:

This utility can be used to convert the **current** file to a different set of units. If the file is in English units, then it can only be converted to metric and vice versa.

Notes:

- The current file should already be saved before accessing the conversion option.
- After conversion, the converted file becomes the current file.
- A prefix is added to the name of the converted file.

Part VI
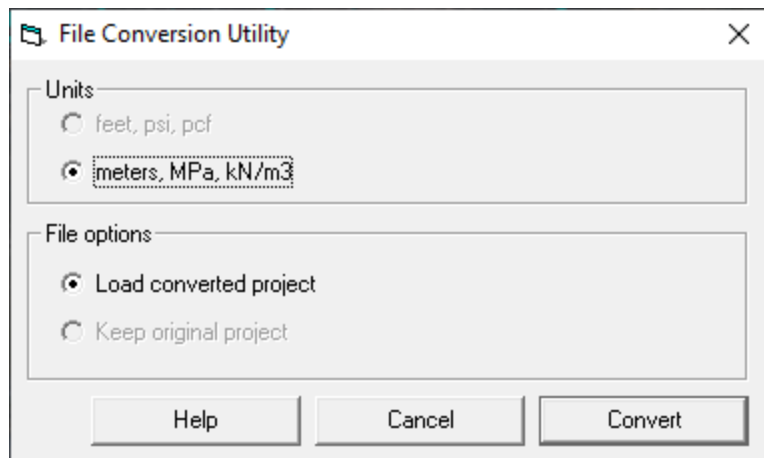
6 The Help Menu

Use the Help menu option to access the following topics:

About AMRS

Disclaimer

Program updates

References

Resource Files

6.1 About AMRS

The "Analysis of Mine Roof Support" (AMRS) program program was developed by Dr. Christopher Mark.

This Windows implementation (version 1.0) was developed by Dr. Zach Agioutantis, University of Kentucky.

The help and support of Dr. Christopher Mark and Mr. Ryan Stephan during all stages of this project is greatly appreciated.

The authors would like to thank J.H Fletcher and Co for the photograph used on the cover of the manual and on the main program screen.

6.2 Disclaimer

This software is provided 'AS IS' without warranty of any kind including express or implied warranties of merchantability or fitness for a particular purpose. By acceptance and use of this software, which is conveyed to the user without consideration by the developers, the user expressly waives any and all claims for damage and/or suits for personal injury or property damage resulting from any direct, indirect, incidental, special or consequential damages, or damages for loss of profits, revenue, data or property use, incurred by the user or any third party, whether in an action in contract or tort, arising from access to, or use of, this software in whole or in part.

See also: Program Updates

6.3 Program Updates

The AMRS program features an automatic update mechanism. Each time the AMRS program is executed and the computer is connected to the internet, AMRS automatically

checks whether a new release is available. The user is then asked whether to download and install the new release.

Users may opt out of the automatic program updates (not recommended).

Users may manually check whether there are updates available that can be downloaded and installed by clicking on *Check for Updates* on the form below.

The AMRS program was officially released in June 2020. Minor updates may be issued periodically.
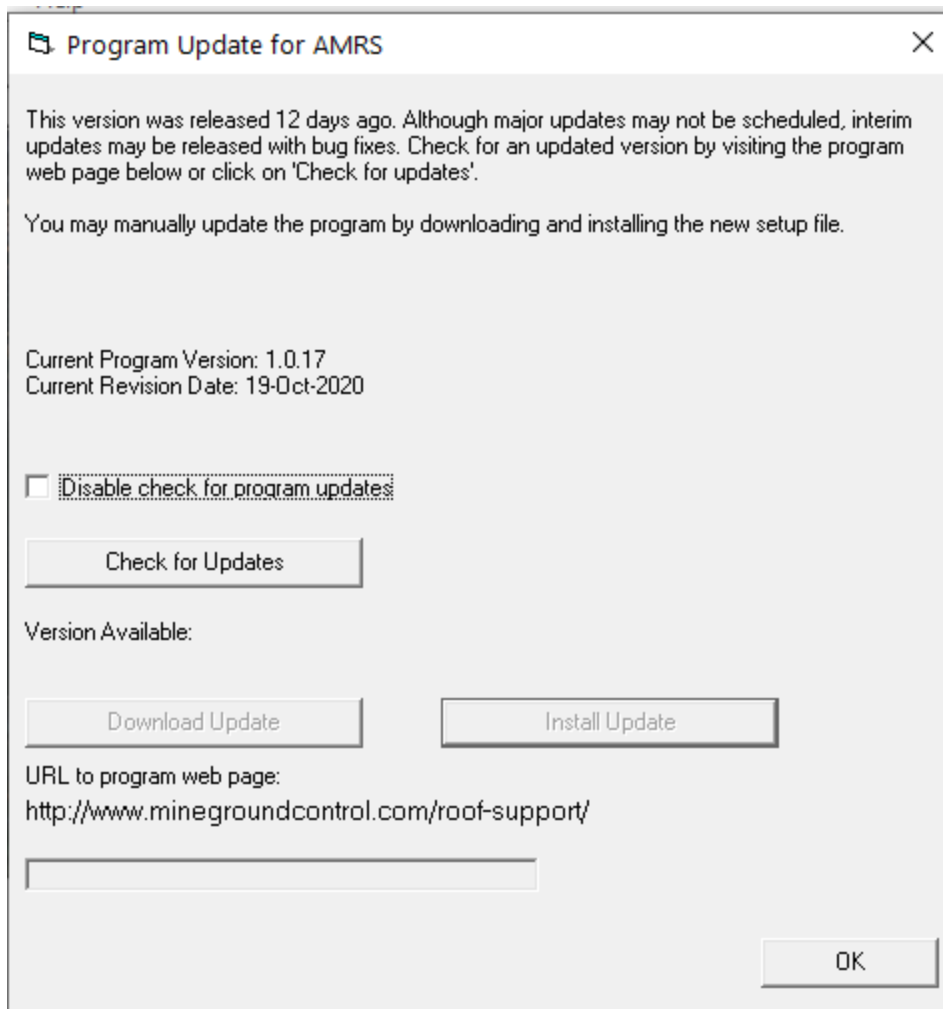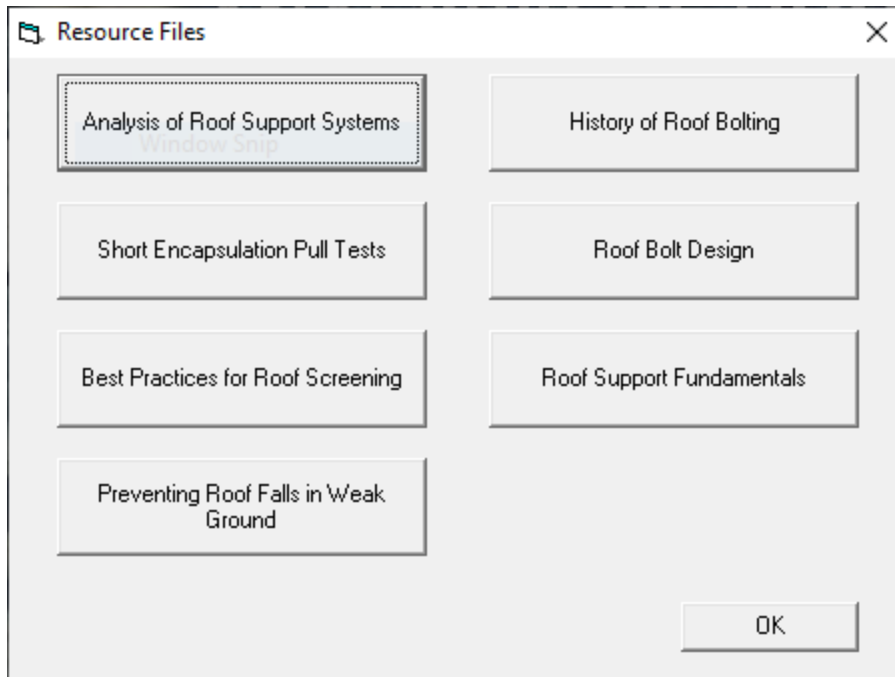

AMRS can also be downloaded from the www.minegroundcontrol.com website.

6.4 Resource Files

A number of resource files is distributed with the AMRS program.

The user can access these files by clicking on the respective command button.

6.5   References

Colwell M, Frith R [2009]. ALTS 2009 - A Ten Year Journey. Proceedings of the 2009 Coal Operators' Conference, Wollongong, NSW, pp. 37-53.

Mark C [2000]. Design of Roof Bolt Systems. Paper in New Technology for Coal Mine Roof Support, Proceedings of the NIOSH Open Industry Briefing, NIOSH IC 9453, pp. 111-132.

Mark C [2016]. The Science of Empirical Design in Mining Rock Mechanics. International Journal of Mining Science and Technology, Elsevier, v26, pp. 461-470.

Mark C, Barczak TM [2000]. Fundamentals of Coal Mine Roof Support. New Technology for Coal Mine Roof Support, Proceedings of the NIOSH Open Industry Briefing, NIOSH IC 9453, pp. 23-42.

Mark C, Molinda GM, Dolinar DR [2001]. Analysis of Roof Bolt Systems. Proceedings, 20th International Conference on Ground Control in Mining, Morgantown, WV, pp. 218-225.

Mark C, Molinda GM [2005]. The Coal Mine Roof Rating (CMRR)—A Decade of Experience. International Journal of Coal Geology, vol 64/1-2, pp. 85-103.

Mark C, Gadde M [2008]. Global Trends in Coal Mine Horizontal Stress Measurements. Proceedings, 27th International Conference on Ground Control in Mining, Morgantown, WV, pp. 319-331.

Mark C, Compton C, Oyler D [2002]. Anchorage Pull Testing for Fully-Grouted Roof Bolts. Proceedings, 21st International Conference on Ground Control in Mining, Morgantown, WV, pp. 105-113.

Mark C., Stephan, R. [2019]. Preventing Roof Falls in Weak Ground. Proceedings, 38th International Conference on Ground Control in Mining, Morgantown, WV, pp. 296-300.

Mark C., Stephan, R., Agioutantis Z., [2020]. Analysis of Mine Roof Support (AMRS) for US Coal Mines, Mining, Metallurgy & Exploration (2020) 37:1899–1910.

Molinda GM, Mark C, Dolinar DR [2000]. Assessing Coal Mine Roof Stability Through Roof Fall Analysis. Paper in New Technology for Coal Mine Roof Support, Proceedings of the NIOSH Open Industry Briefing, NIOSH IC 9453, pp. 53-72.

Thomas R [2010]. The Design and Management of Wide Roadways in Australian Coal Mines. Proceedings, 29th International Conference on Ground Control in Mining, Morgantown, WV, pp. 283-293.

Part VII
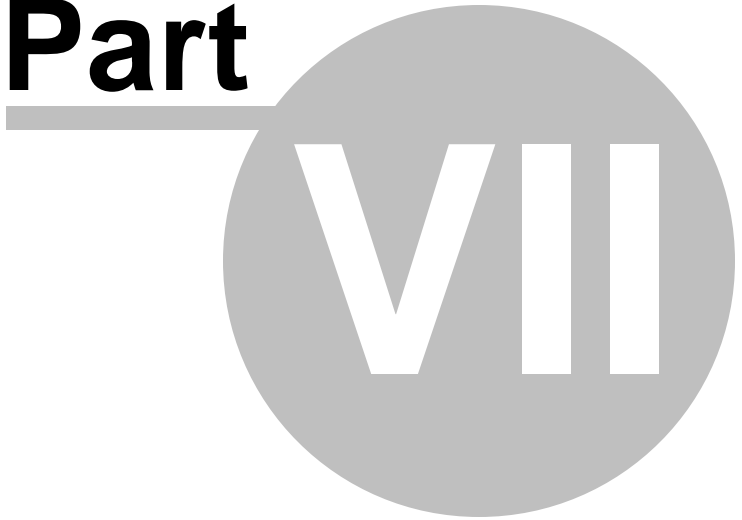
7 Background Information

Roof Support Mechanics

Roof Fall Database

Statistical Analysis

Design of Supplemental (Secondary) Support

Additional Factors to Consider

7.1 Roof Support Mechanics

Roof support design begins with an understanding of how roof bolts support the ground. As illustrated in Figure 4, roof bolts work in several different modes depending on (1) the strength of the roof and (2) the magnitude of the stress in the ground (Mark, 2000).

Suspension and Skin Control: When the immediate roof is a thick, competent sandstone or limestone, roof falls above the bolt anchorage are very rare. Under these conditions, roof bolts still serve the essential purpose of preventing "skin" failures involving thin slabs or blocks of loose rock. Roof bolts also work in suspension when a thin, weak, immediate roof can be suspended from an overlying strong unit (Figure 2).

Beam Building: When no strong, stable unit is within reach, then the bolts attempt to create a "beam." The bolts tie the roof together by maintaining friction on bedding planes, keying together blocks of fractured rock and controlling the dilation of failed roof layers. Stronger, stiffer beams are built with longer bolts, larger diameter bolts, and increased grout length. The density of the support system can also be increased by adding additional bolts to the pattern or reducing the row spacing (Figure 3).

Supplemental (Secondary) Support: Supplemental support is required where the roof is so weak, relative to the ground stresses, that roof bolts alone are not able to prevent roof failure from progressing above the anchorage horizon. In these cases, cable bolts, cable trusses, or standing support carry the dead-weight load of the broken roof, and the roof bolts act primarily to prevent unraveling of the immediate roof. Secondary support is typically planned in advance (and may be installed after initial development), while supplemental support is installed as needed. The terms are sometimes used interchangeably. The AMRS secondary support module can be used for either.

7.2 Roof Fall Database

During the late 1990's NIOSH constructed a roof fall database from 37 coal mines located in all the major US coalfields. The database covered more than 1500 miles of drivage and included 900 roof falls (Molinda et al., 2000). Underground surveys yielded

more than 100 "case histories," each one of which was a portion of a mine defined by its unique geology, depth, roof span, and roof support (Figure 1). For each case history, NIOSH calculated the number of reportable roof falls, the total mining drivage, and the total number of intersections. To ensure comparability across the data, only roof falls occurring within 18 months of development were considered. Roof falls influenced by abutment loads due to mining activity, such as longwall retreat or multiple seam interactions, were also excluded from the data base, as were those associated with large scale geologic discontinuities like faults or sandstone channel margins. NIOSH expanded the data base during the 2000's to include another 800 miles of mining drivage and 600 roof falls from another 12 mines known for weak roof conditions.

NIOSH used the original database to develop the Analysis of Roof Bolt Stability (ARBS) (Mark et al., 2001). ARBS suggested a level of roof support based on the depth of cover and the roof quality. Suggestions regarding the intersection span and the bolt length were also derived from the data. ARBS was developed before cable bolts came into wide use, however, so it was not suitable for weak roof/high stress applications. Roof fall rates were also much higher 20 years ago than they are today, so the ARBS suggested Stability Factor (SF) of 1.2 also needs to be updated.

Each of the case histories in the NIOSH database was defined by four descriptive parameters: Stress level, roof rock quality, roof span, and roof support density. The final parameter was the outcome. NIOSH used the number of roof falls per 10,000 feet of drivage to determine whether a case history was successful or not (Mark et al., 2001). The current study focusses on intersection stability, and the outcome is the number of four-way intersection roof falls per 1000 intersections developed. Those case histories with fewer than two falls per 1000 four-way intersections were considered successful, while greater roof fall rates were considered unsuccessful. These new criteria are more conservative than those used in the NIOSH study, reflecting the large decrease in the roof fall rate since 2001.

7.3   Statistical Analysis

Statistics are essential to interpreting large, multi-variate ground control data sets. They are the tools that science has developed to deal with uncertainty and probability. Statistics have helped develop a number of powerful ground control design techniques that are widely used around the world. However, it essential to keep in mind that in ground control, statistical analysis assists engineering judgment; it does not substitute for it (Mark, 2016).

The first step in a statistical analysis is to explore correlations between variables within the data set. In general, when two variables are highly correlated with one another, both cannot be used in the model. In the roof fall database, the CMRR is highly correlated with both the intersection span (see Figure 5) and with the Primary Support Rating index (PSUP). It seems that where the roof was weak to start with, the mines had responded by installing more roof bolts and by narrowing their intersections. This fact poses particular problems from a statistics standpoint, because some of the mines with the

highest roof fall rates also used the most roof support and had the smallest intersections.

Also note that in any regression analysis, a variable that is used in the model must have a linear effect on the outcome. The CMRR's effect is nonlinear, however, because a 10-point decrease in the CMRR from 40 to 30 has a much greater effect on roof stability than a 10-point decrease from 80 to 70. To address this, the CMRR was "transformed" into a new variable called $LnCMRR20 = Ln(CMRR-20)$.

The first goal of the analysis was to help quantify the boundaries between the three roof support regimes shown on Figure 4. Logistic regression (LR) was used to model the data, because it is the technique of choice when the outcome is binary (like "successful" and "unsuccessful"). The LR model that fit the data best was used to derive the following equation:

$$LnCMRR20 = 0.277\ Ln(H) + 1.64 \tag{5a}$$

Equation (5a) is shown on Figure 6 as the "Discriminant." It minimizes the likelihood of misclassifications, meaning in this case that a success is about as likely to be misclassified as a failure.

Figure 6 also shows two other lines that are parallel with the discriminant. All the cases above the upper line are successful, so this is the estimated boundary between the Suspension and the Beam Building regimes:

$$LnCMRR20 = 0.277\ Ln(H) + 1.87 \tag{5b}$$

Nearly all the cases below the lower line are unsuccessful. This therefore seems like a reasonable lower limit for typical US roof bolting support systems, which is the boundary between the Beam Building and Supplemental Support regimes:

$$LnCMRR20 = 0.277\ Ln(H) + 1.37 \tag{5c}$$

Figure 6 can be used to derive a pseudo-discriminant equation that includes PSUP. Using the data in Table 4, the level of roof support for the upper line in Figure 6 (equation 5b) corresponds approximately to PSUP=3. The lower line, equation (5c), corresponds to approximately PSUP=12. So for a depth of 600 feet, for example, the suggested PSUP (PSUPg) =3 when the CMRR=58, and PSUPg=12 when the CMRR=43. Connecting these two points and combining the result with equation (5), the PSUPg for a depth of 600 feet can be related to LnCMRR20 as:

$$LnCMRR20 = 0.277\ Ln(600) - 0.056(PSUPg) + 2.04 \tag{6a}$$

Equation (6a) can be rearranged to solve for PSUPg at a depth of 600 feet:

$$PSUPg = 4.95*(Ln(600)) - (17.9*(LnCMRR20)) + 36.4 \tag{6b}$$

Figure 7 illustrates equation (6). To create the figure, the depths of cover in all of the case histories were normalized to 600 feet, using the (4.95*(Ln(Depth))) factor from equation 6b. Figure 7 shows that equation 6 seems to fit the data quite well, separating the successful case history cases from the unsuccessful ones.

Equation 6b can be generalized to predict PSUPg at any depth. A span factor is also included that uses equation (2) to adjust the suggested support, similar to the one previously used in ARBS (Mark et al., 2001). The final AMRS equation that suggests the appropriate level of primary support (PSUPg) is:

$$PSUPg = SF * [1+((SumD^2 -(SumDg)^2)/ (SumDg)^2)] * \\ [4.95*(Ln(Depth)) - 17.9*(LnCMRR20) + 36.4] \qquad (7)$$

7.4   Design of Supplemental Support

When the rock is too weak and the stress too high, roof bolts alone are unlikely to be successful in preventing roof falls. In this "Supplemental Support" regime, the support should have the capacity to carry the rock load, which is the dead weight of the broken roof that has potentially separated from the more stable overlying rock mass. The rock load can be suspended from the stable portion of the rock mass using intrinsic supports (such as cable bolts, truss bolts, or roof bolts), or the load can be transmitted to the floor by standing supports.

The rock load can be calculated from the geometry of a potential roof fall. Different equations are needed for straight segments (entries and crosscuts) and for intersections. The calculation considers the span, the thickness of roof to be supported, and the typical profile of roof falls (Figure 9). When determining the thickness of roof to be supported, mine-specific historical roof fall heights should be evaluated. In addition, the design should consider the height of any known separations, the length of the primary roof support, and the free-length of the cable bolts.

$$RockLoad_{Straights} = \gamma * [(We * ht) - ((ht)^2 * \tan \theta)]$$

$RockLoad_{Intersections}$

$$= \frac{\gamma * ht}{3} \left\{ \left[\left(\frac{SumD^2}{4} \right) - \left(\frac{\sqrt{0.5} * ht * SumD}{\tan(90 - \theta)} \right) - \left(\frac{\sqrt{0.5} * ht * SumD}{\tan(90 - \alpha)} \right) \right. \right.$$
$$\left. + \frac{4(ht)^2}{(\tan(90 - \theta)) * (tan90 - \alpha)} \right]$$
$$\left. + \left[\left(\frac{SumD^2}{8} \right) - \left(\frac{ht * SumD}{\sqrt{8} * (\tan(90 - \alpha))} \right) - \left(\frac{ht * SumD}{\sqrt{8} * (\tan(90 - \theta))} \right) \right] \right\}$$

where
$\qquad$ = rock unit weight (tons/ft^3)
ht $\qquad$ = rock load height (ft)
We $\qquad$ = entry width (ft)
SumD = sum of diagonals (ft)
$\qquad$ = roof fall angle from entry (degrees)
$\qquad$ = roof fall angle from crosscut (degrees)

The capacity of a supplemental support system is determined by the capacity of an individual support and the number of supports in each row or intersection.

Equation (8) calculates the Stability Factor (SF) comparing the support capacity and the rock load per unit length of entry:

$$SF = (n * C) / (Spc * RockLoad_{Straights}) \qquad\qquad (8)$$

where:
n = Number of supports in a row
C = Capacity of an individual support (tons)
Spc = Spacing between rows of supports (ft)

Equation (9), for intersections, uses the total number of supports (Nint) that are installed and the capacity (C) of each support. The rock load is calculated using two roof fall angles, one perpendicular to the entries, and the other to the crosscuts, as explained above

$$SF = (Nint * C) / RockLoad_{Intersections} \qquad\qquad (9)$$

where:
Nint = total number of supports
C = Capacity of an individual support (tons)

7.5 Additional Factors to Consider

Providing for adequate support system capacity addresses only one mode of failure, however. In general, the design of intrinsic roof support systems must consider five potential failure modes (Figure 12):

1. **Unravelling of the rock mass between the bolts.** Localized loose rock between the bolts creates a skin control hazard, and more widespread failure can cause the heads of the bolts to lose contact with the roof. Such failure can progress upward to defeat the entire support system. Unravelling is prevented with surface control, which can include straps, surface control pans, mesh, shotcrete, or similar devices. In general, roof support products that provide greater surface coverage result in better confinement and reduce unravelling roof failures.

2. **Head/plate failure.** Bolt head failure is very unusual, though not unheard of. Roof bolt manufacturing specifications address this by requiring that the capacity of the bolt head exceed the capacity of the rod.

3. **Bar failure.** Calculations comparing the rock load to the roof bolt system capacity are aimed at preventing the bolts from breaking due to excessive applied loads. Not only should the tensile capacity of the bar exceed the load, but the bolt's shear strength also should be adequate to respond to the potential lateral rock movement.

4. **Anchor failure.** Regardless of the type of bolt, some portion of it functions as an anchor. A bolt will pull out of the roof when its anchor fails before the bolt breaks. For resin grouted rods, typically the upper foot or so serves as the anchor, while for cable bolts the anchor typically requires three or four feet. The anchorage capacity should exceed the design capacity of the bolt, regardless of the type of anchor (mechanical, resin, or combination). Effective anchorage is most difficult to achieve in weak rock, and cable bolt anchorage failures have occurred in the Illinois Basin even with four feet of grouted length. Short encapsulation pull tests can be used to check that the necessary anchorage is being achieved (Mark et al., 2002). The quality of the installation can also have a large effect on the capacity of the anchor.

5. **Length failure.** Length failure occurs when roof failure occurs at or above the bolt's anchorage zone. The length of cable bolts, for example, should allow for adequate anchorage above the rock fall envelope. Truss bolts achieve this by anchoring in the stable rock above the pillar, though this is problematic in intersections.

The stiffness of roof supports is another important consideration. Stiffness may be defined as the amount of ground movement that must occur in order to generate resisting loads from the support. The stiffness of standing supports in particular varies considerably between different types of support. Indeed, the load-bearing capacity of a standing support cannot really be defined without also specifying the expected convergence. Cable bolts are also less stiff than solid bar bolts, because the design of the strands, the length of the ungrouted portion, and the overall length all allow cable bolts to stretch more in response to the same applied load. Cable bolts are an inherently soft support system, which makes them suitable for suspending a rock load from stable ground.

Part VIII
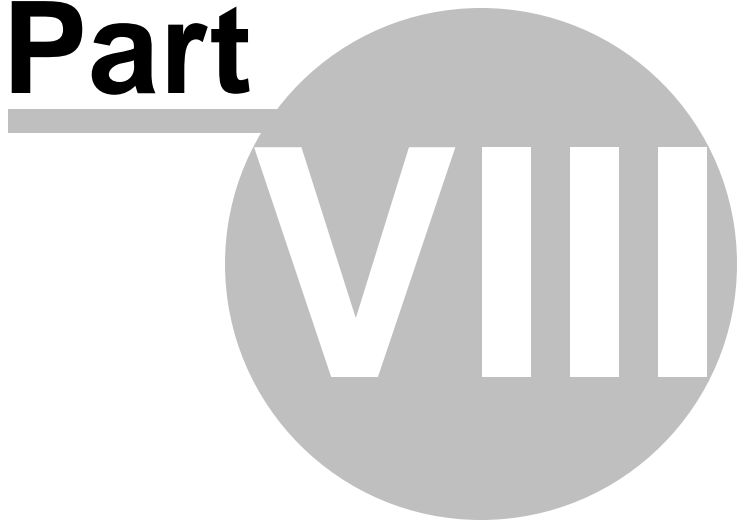
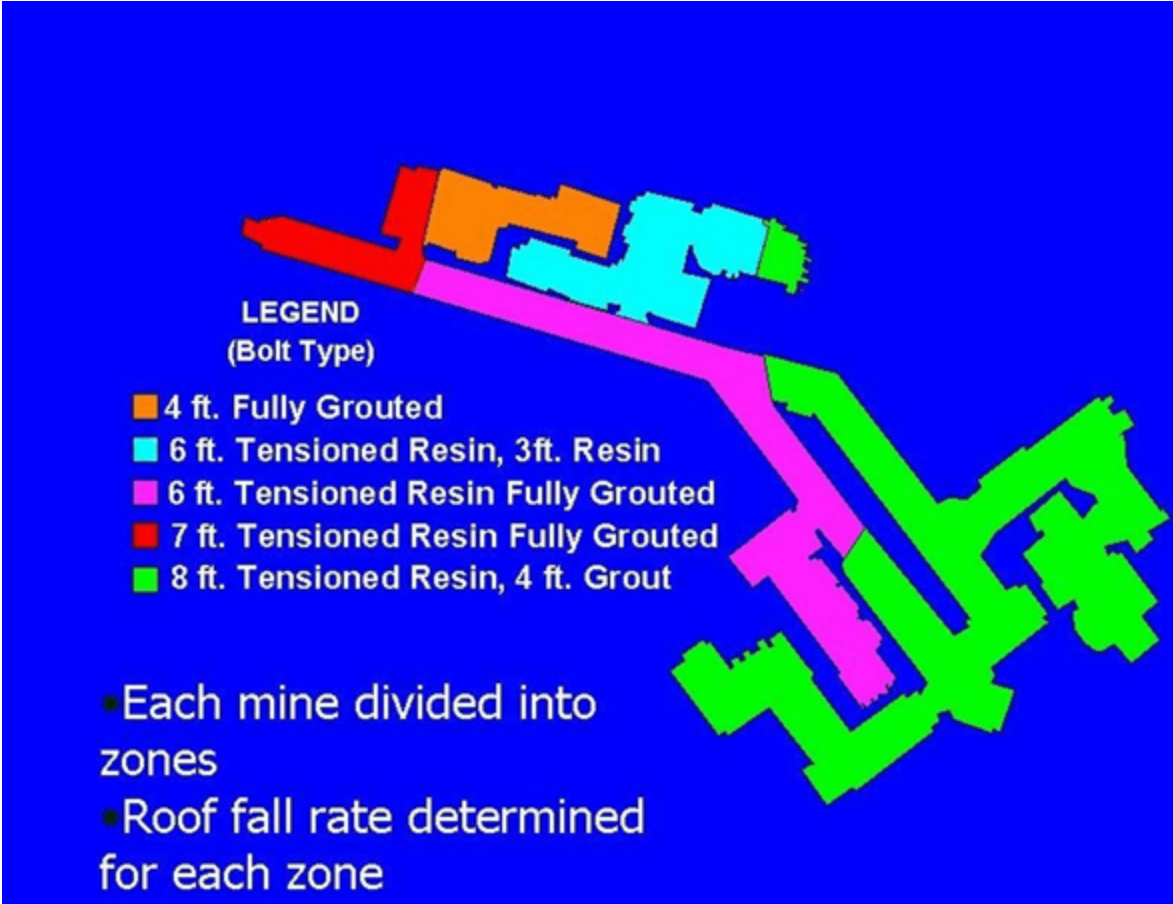# 8   List of Figures

8.1   Figure 1

Figure 1: Statistical Study
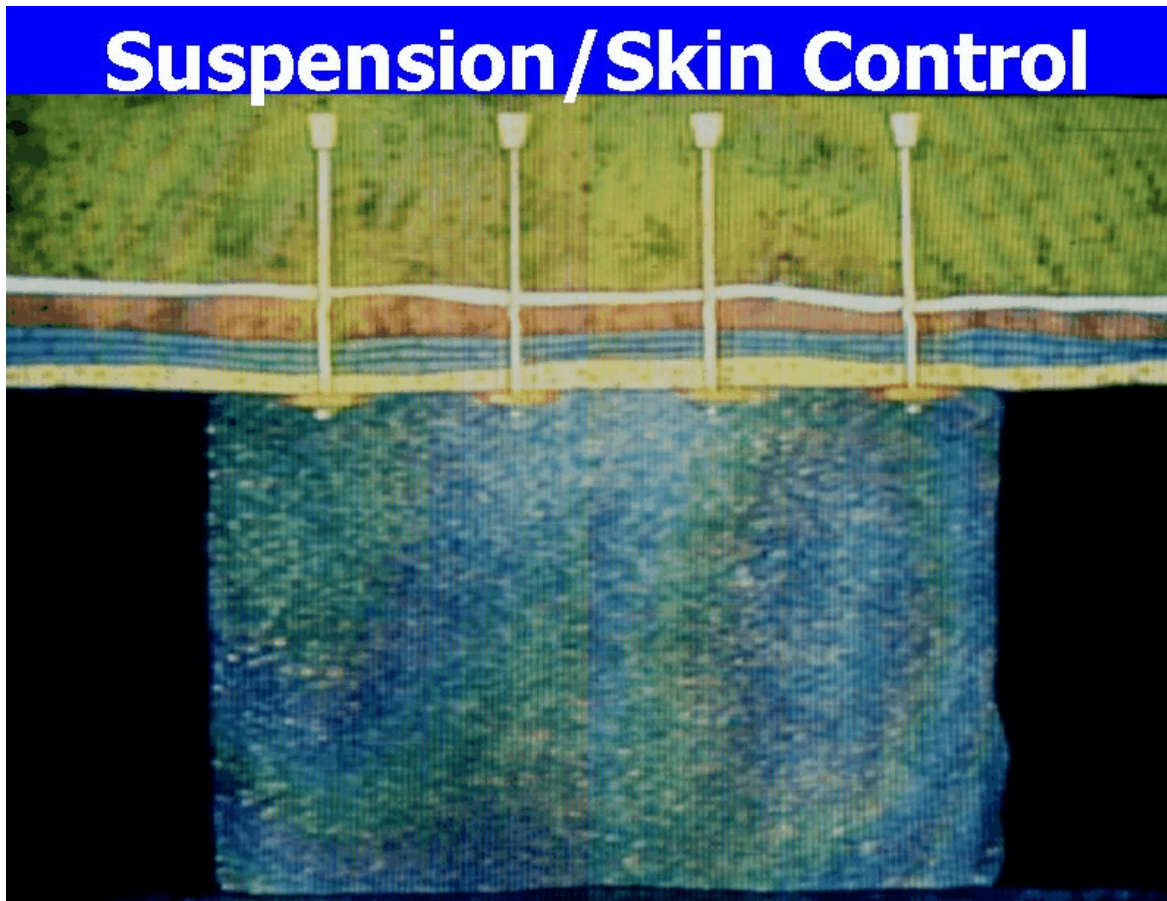
8.2   Figure 2

Figure 2: Skin Control and Suspension
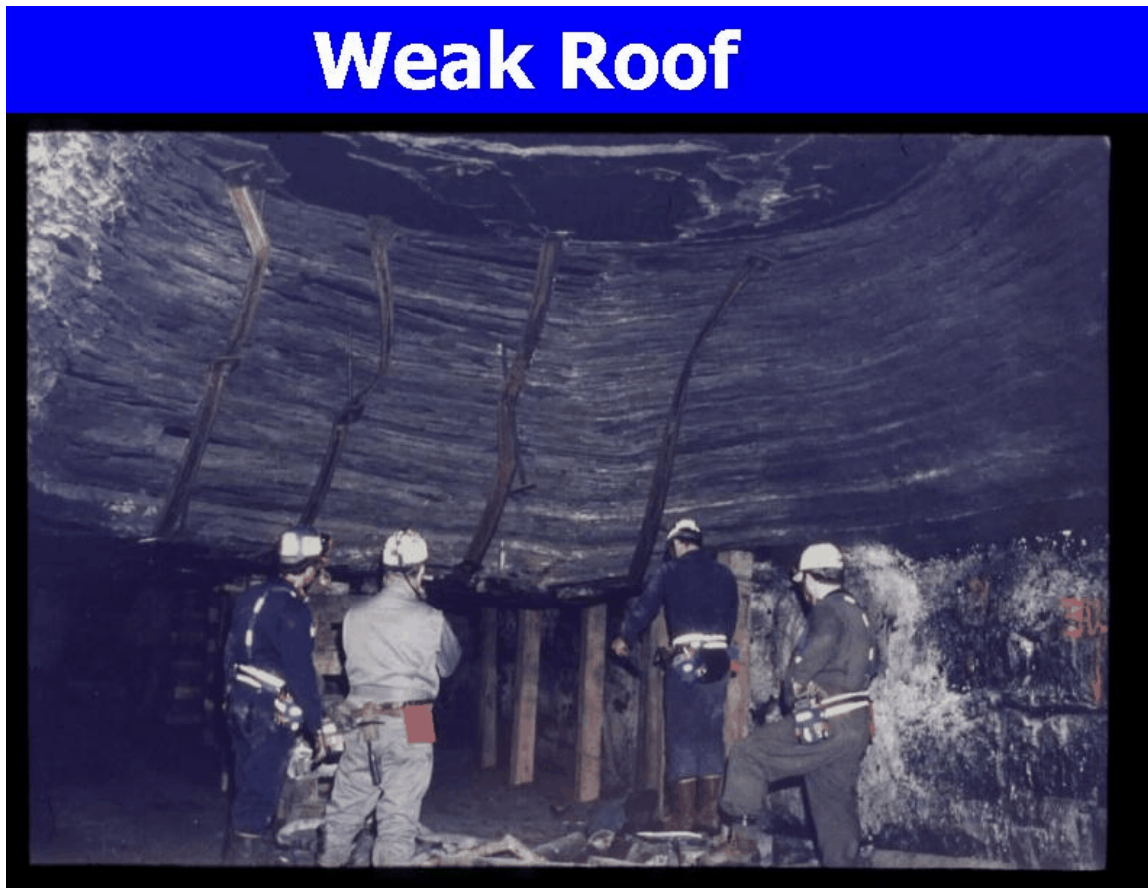
8.3   Figure 3
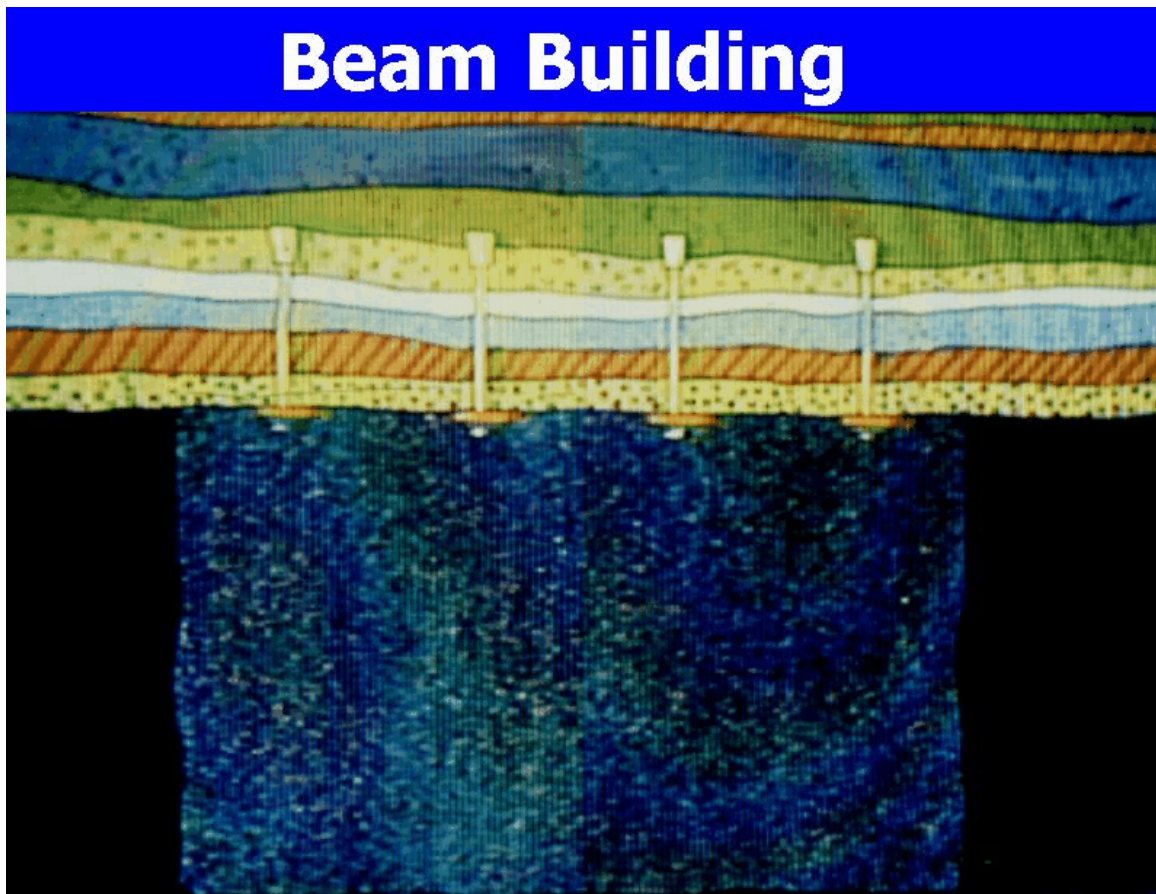

Figure 3a: Beam Building (1/2)

Figure 3b: Beam Building (2/2)
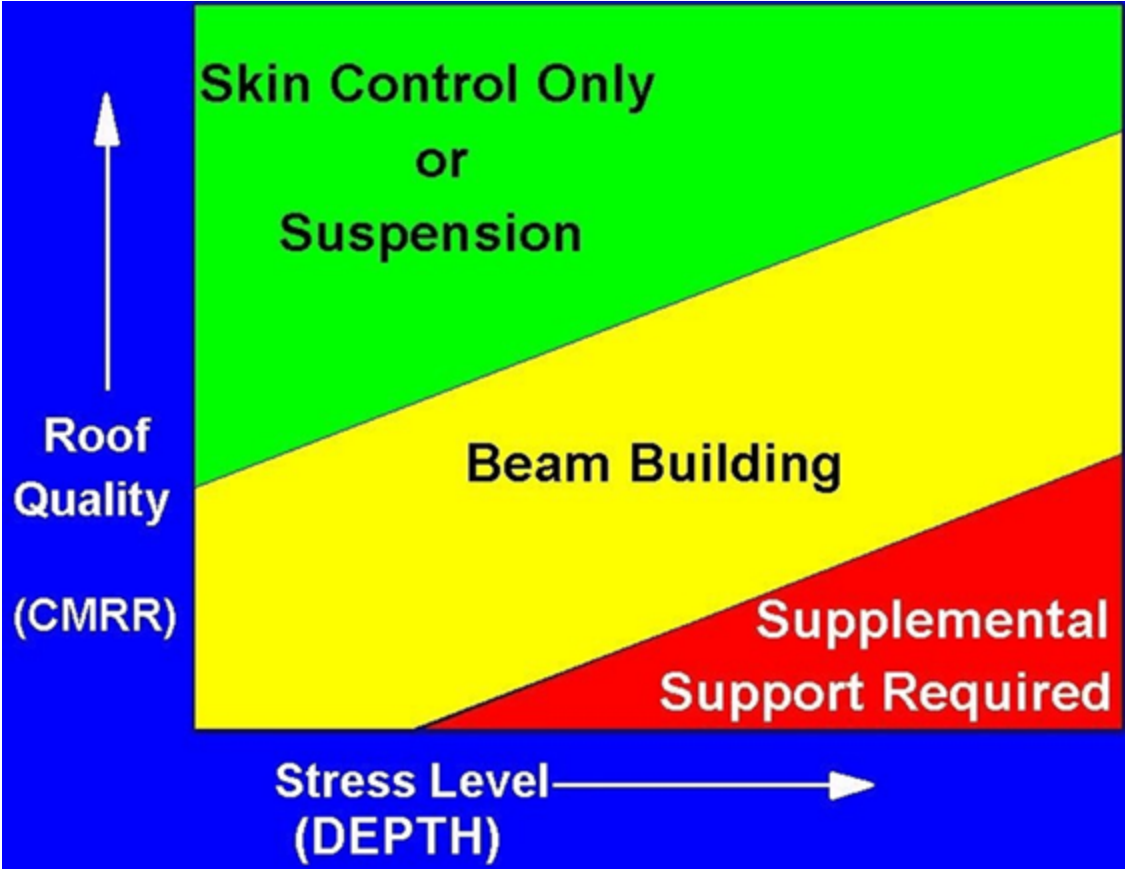
8.4   Figure 4

Figure 4: Roof support mechanisms determined by stress level and roof quality (after Mark, 2000)
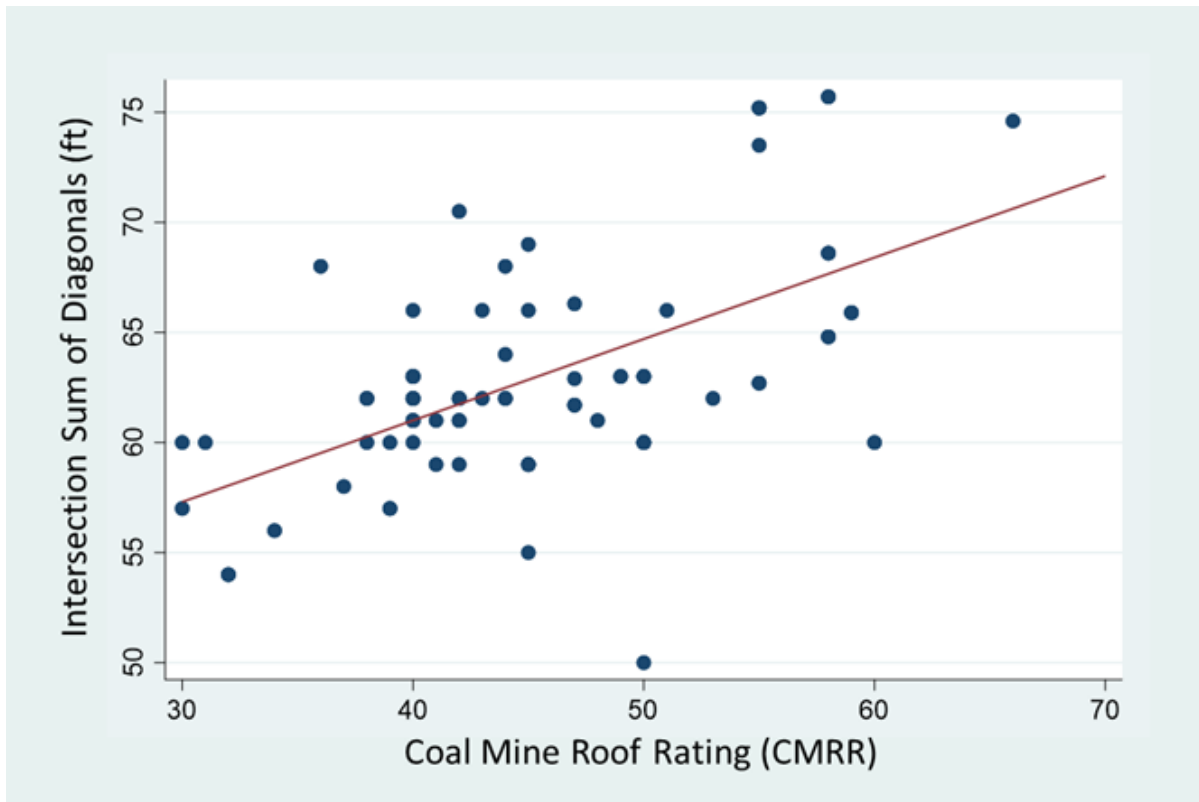
8.5 Figure 5

Figure 5: Correlation between measured intersection diagonals and the CMRR in the expanded data base (excluding cases where CMRR>70 or the roof fall rate was exceptionally high).

8.6 Figure 6
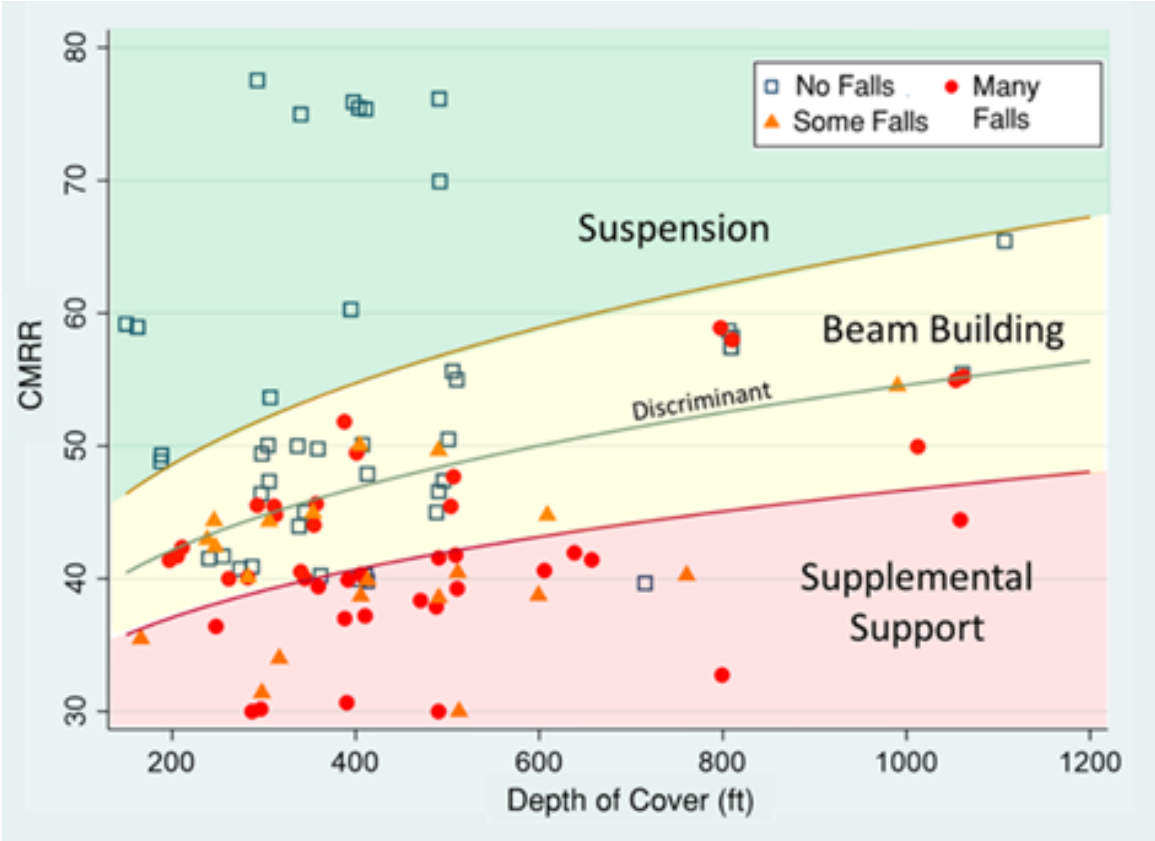
Figure 6: The roof bolt support case histories, showing the discriminant equation and the estimated boundaries between the three roof support regimes.

8.7 Figure 7
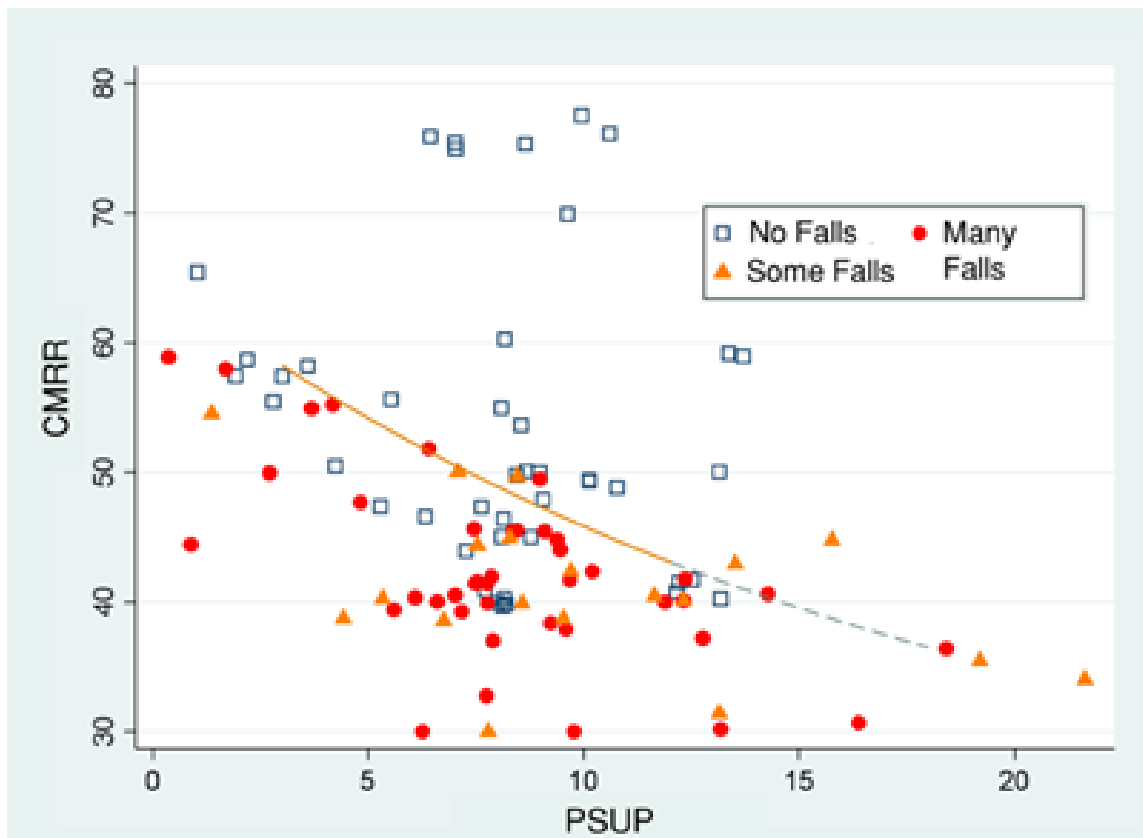
Figure 7: Suggested PSUP for depth of cover = 600 feet. The solid gold line extends covers the range of PSUP from 3 to 12.

8.8   Figure 8
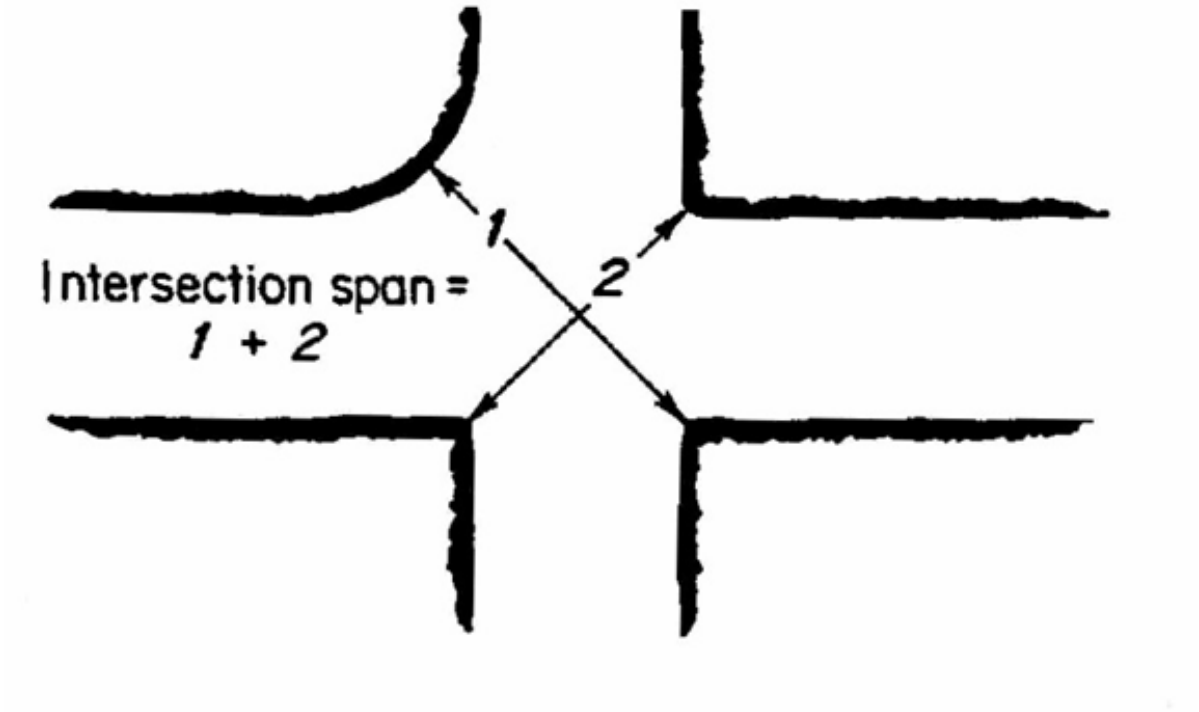
Figure 8: Sum of the Diagonals or Intersection Span

8.9 Figure 9
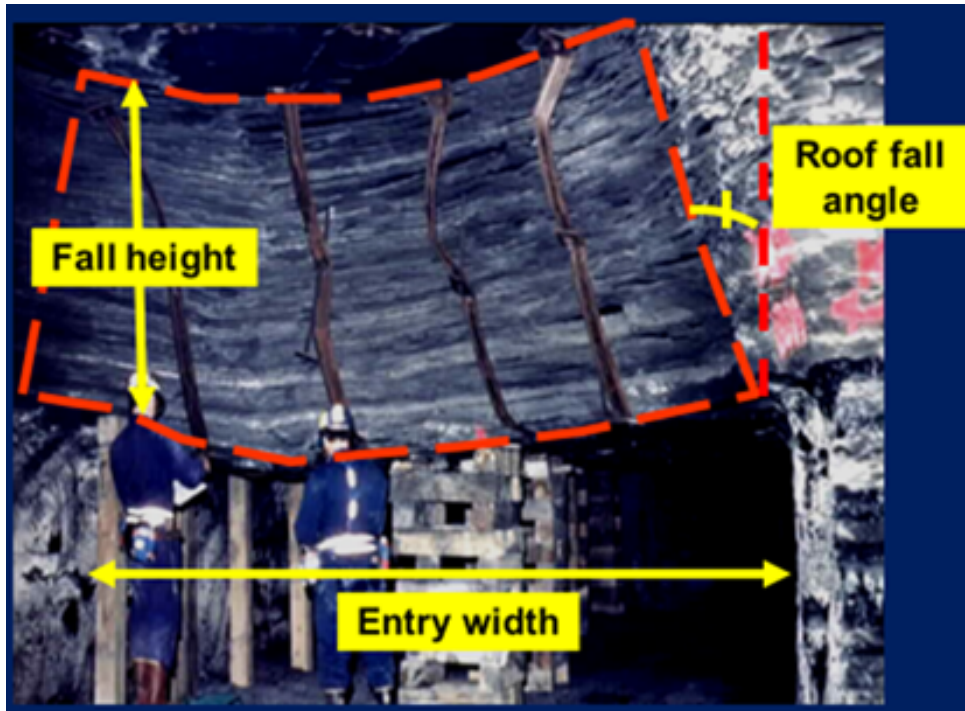
Figure 9a: Estimation of rock load to be carried by secondary support (1/2)
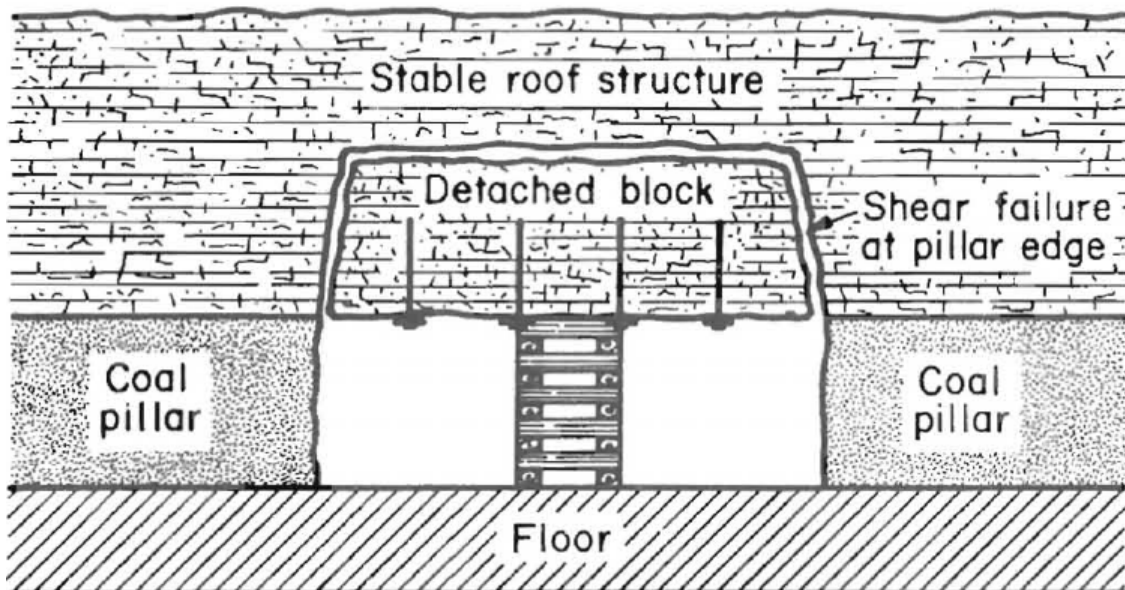
Figure 9b: Estimation of rock load to be carried by secondary support (2/2)

8.10   Figure 10

Figure 10: Comparison between PSUP values suggested by AMRS and ARBS (SF=1.5)

8.11 Figure 11
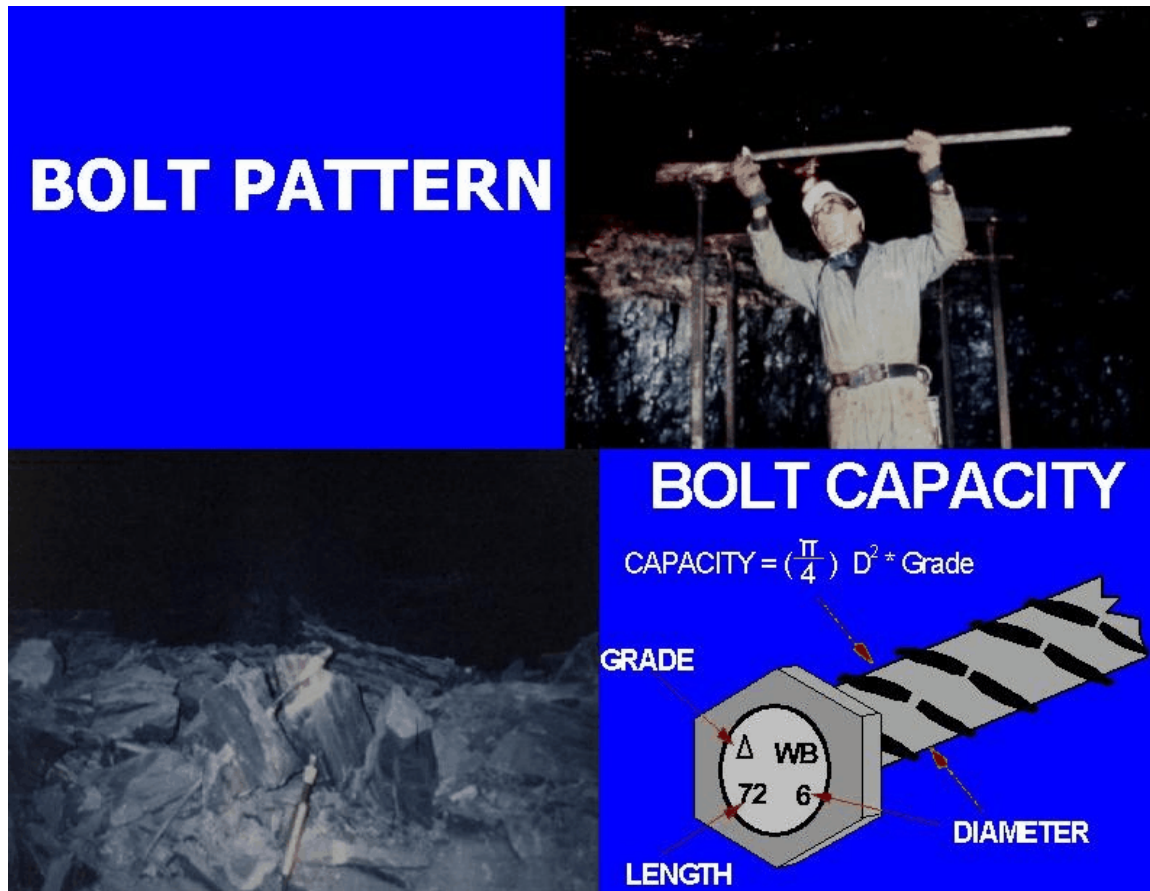
Figure 11: Capacity of the Roof Bolt

8.12   Figure 12
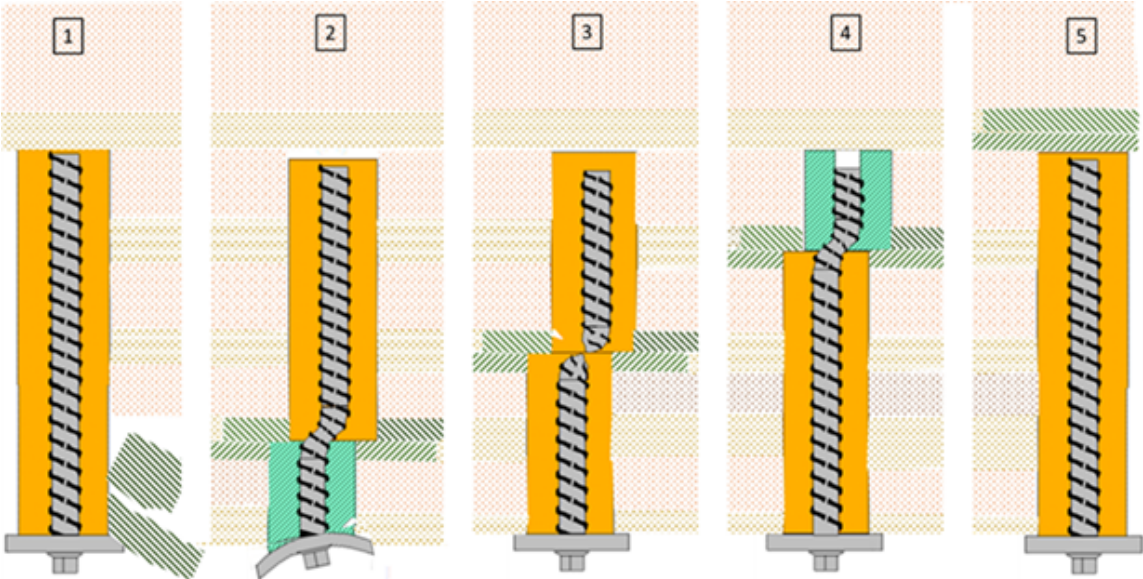
Figure 12: Roof bolt failure modes. (1) Unravelling (2) Head/Plate (3) Bar (4) Anchor (5) Length

8.13   Figure 13
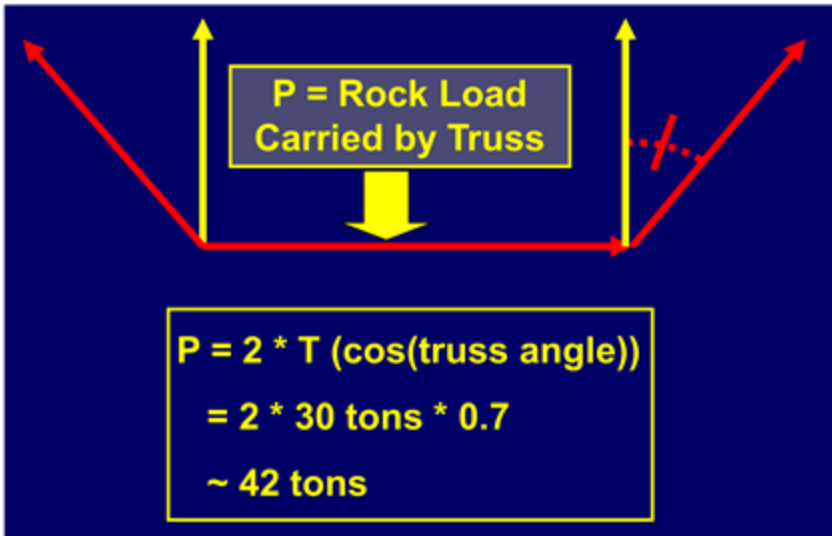
Figure 13: Calculation of the support capacity of a roof truss.

Index

- A -

- B -

- C -

- D -

- E -

- F -

- G -

- H -

- I -

- L -

- M -

- O -

- P -