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An Area-Based Calculation of the Analysis of Roof Bolt Systems (ARBS)

Aanand Nandula

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An Area-Based Calculation of the Analysis of Roof Bolt Systems (ARBS)

Aanand Nandula

Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mining Engineering

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2017

Keywords: CMRR, Coal Mine Roof Rating, Analysis of Roof Bolt Systems, ARBS,
Stability mapping, LaModel stress analysis
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Abstract

An Area-Based Calculation of the Analysis of Roof Bolt Systems (ARBS)

Aanand Nandula

The objective of this research is to develop a software tool, which will assist in the area-wide calculation of ARBS while incorporating more detailed/accurate stress, varying CMRR and intersection span inputs. This tool imports the overburden, abutment and multiple-seam stresses as obtained by the boundary-element program LaModel and is converts them to a “pseudo-depth” which is used as the depth input to the ARBS calculations. In addition, available geologic data at the mine can be used to determine an area-based CMRR, and mine design information can be used to determine an area-based intersection span for input to the calculation. This tool is incorporated in the recently modified Stability Mapping program (StabMap) which, as part of this development effort, has been upgraded to readily accept area-based inputs from: SurvCADD’s geologic grids for calculating an area-based CMRR, LaModel’s stress grids for determining an area-based pseudo-depth, and user defined grids for specifying an area-based intersection span. Finally, the StabMap program is now designed to take the appropriate pseudo-depth, CMRR, and intersection span grids to calculate an area-based ARBS support intensity. This final area-based ARBS grid can then be plotted, analyzed and overlaid on the mine map for optimum presentation to production personnel.

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Table of Contents

Page

Abstract.....	ii
Acknowledgements	iii
Table of contents	iv
List of figures	vi
List of tables	viii
Chapter 1: Introduction.....	1
1.1 Background.....	1
1.2 Statement of problem.....	2
1.3 Scope of work.....	3
Chapter 2: Literature Review.....	4
2.1 General	4
2.2 Coal Mine Roof Rating (CMRR)	5
2.2.1 Components of CMRR	6
2.2.1.1 Discontinuities	6
2.2.1.2 Discontinuity intensity.....	7
2.2.1.3 Compressive strength.....	7
2.2.1.4 Moisture sensitivity	8
2.2.1.5 Non-unit information	8
2.2.2 CMRR calculations	9
2.2.3 CMRR program	12
2.2.4 Areal CMRR calculation	13
2.3 Analysis of Roof Bolt Systems (ARBS).....	19
2.3.1 ARBS parameters	19
2.3.1.1 Effect of roof quality (CMRR)	19
2.3.1.2 Effect of stress (Depth of cover)	20
2.3.1.3 Effect of entry design (Intersection span).....	21
2.3.2 ARBS calculations.....	22
2.4 LaModel	24
2.5 Stability mapping.....	25

2.6 AutoCAD and customization.....	27
2.6.1 ObjectARX programming.....	28
Chapter 3: Design of areal ARBS.....	29
3.1 General	29
3.2 Data format	29
3.3 Data requirements.....	30
3.4 Grid read and write	31
3.5 Program creation	32
Chapter 4: Implementation of areal ARBS.....	33
4.1 General	33
4.2 User interface	33
4.2.1 Loading StabMap	33
4.2.2 Areal ARBS module	35
4.3 Areal ARBS calculations.....	41
Chapter 5: Case study.....	42
5.1 Introduction	42
5.2 Case study	42
5.2.1 Background.....	43
5.2.2 CMRR grid generation	46
5.2.3 Pseudo-depth grid generation	51
5.2.4 Intersection span grid generation.....	55
5.2.5 Final ARBS grid generation	56
Chapter 6: Summary and conclusions	59
6.1 Summary.....	59
6.2 Conclusions	60
6.3 Ideas for future work	61
References	63

List of Figures

Page

Chapter 2: Literature Review

2.1 Components of CMRR	6
2.2 Visual classification of roughness	7
2.3 Ball peen hammer impact test	8
2.4 CMRR field data sheet	10
2.5 Final roof rating calculation sheet	11
2.6: Underground information form, CMRR program	12
2.7: Drill core information form, CMRR program	13
2.8: General information form.....	15
2.9: Core data input form	16
2.10: Underground observation input form	16
2.11: Discontinuity input form	17
2.12: Final parameters form	18
2.13: Roof fall rates for different CMRR values	20
2.14: Skin control	21
2.15: Suspension	21
2.16: Beam Building	21
2.17: Supplemental support	21
2.18: Roof fall cases vs Intersection Span	22
2.19: Schematic of laminated overburden	24
2.20: Hazard Map	26

Chapter 4: Implementation of areal ARBS

4.1: Loading stability application	34
4.2: StabMap menu system.....	34
4.3: Flowsheet to generate CMRR grid	36
4.5: Transfer LaModal/MULSIM results	37
4.6: Grid utility form	38

4.4: Flowsheet to generate pseudo-depth grid	39
4.7: Flowsheet to generate ARBS grid	40
4.8: ARBS input form	41
Chapter 5: Case study	
5.1: Mine location site	43
5.2: Topography over B and D seam	45
5.3: Stratigraphic column of Bowie mine	45
5.4: Sandstone channels and ride, interburden.....	46
5.5: Interburden thickness grid	47
5.6: Rider thickness grid	48
5.7: Sandy mudstone thickness grid	49
5.8: Final CMRR grid.....	51
5.9: Overburden stress grid.....	52
5.10: Multiple seam stress grid.....	53
5.11: In situ stress grid.....	54
5.12: Pseudo-depth grid	55
5.13: ARBS input form.....	57
5.14: Final ARBS grid	58

Chapter 1

Introduction

1.1 Background

Owing to the high demand for coal, the decades from 1930 to 1950 witnessed a major technological advance in the U.S mining industry in the process of coal extraction which eventually led to the introduction of roof bolt systems to tackle the number of roof fall related injuries. However, they did not totally eliminate roof fall problems. According to MSHA's preliminary accident reports, during the period of 1995 to 2017, roof falls have resulted in 102 fatal injuries contributing to a significant 25% of total underground coal mine fatalities (MSHA, 2017). One of the identified reasons for the incidents was lack of a scientific basis in designing the roof bolt systems. Since the inception of roof bolt systems in the mining industry, they were primarily designed through a trial-and-error process whereby mine operators reacted to worsening roof conditions by putting more support into the area. To address the lack of a universal design method for roof bolts, the National Institute for Occupational Safety and Hazard (NIOSH), released a software program, Analysis of Roof Bolt Systems (ARBS), which uses CMRR, depth of cover, and intersection span and provides a numerical value for the required intensity of roof bolts in a mine.

Since its introduction, Coal Mine Roof Rating (CMRR) has been widely used to assist in understanding the roof rock quality based on the geologic data (Molinda and Mark, 1994; Molinda and Mark, 1996; Molinda et al., 2001; Mark et al., 2002). However, there could be a significant change in the geology throughout the mine property. With the help of a more recently developed program the variations in CMRR over a wide area can be tracked and analyzed for designing roof support systems (Petrovich, 2006). In addition, numerical analysis modelling tools, such as LaModel, are being widely

used to analyze the effect of geo-mechanical influences such as overburden and multiple seam stresses over the stability of the mine openings and hence assisting in providing better roof reinforcements.

As a response to the need of calculating area wide ARBS value, there was a need for a tool which can combine both geologic characteristics and stress influences. The Stability Mapping program, StabMap, contains various functionalities to automatically collect and input the geologic information and integrate LaModel results to generate a stability index for different areas of the mine (Wang and Heasley, 2005). The flexibility in StabMap customization provides an opportunity to add new functionalities. With this advantage, it is logical to use this program as a platform to develop an areal ARBS tool which will enable the mine engineer to greatly reduce time and effort in data collection by taking advantage of existing geologic data and integrate detailed stress effects for potentially more accurate estimation of ARBS intensity values.

1.2 Statement of problem:

The Analysis of Roof Bolt Systems (ARBS) provides a preliminary guideline for designing bolt systems, and it has been widely accepted by the mining industry. Currently, the calculations for the bolt density requirements are performed for a single location with a given CMRR and depth of cover. Determining the different support density for every area of the mine where there is a different depth and/or geology can be a daunting task for the mine personnel. Also, in many mines with multiple-seams and/or full extraction mining, the mine stresses include multiple-seam and abutment stress in addition to the overburden stress. To provide a solution to these limitations with ARBS, this thesis proposes to introducing an area-wide calculation ARBS and including more accurate detailed/accurate geology and stress determinations in the calculations.

1.3 Scope of Work

The objective of this research is to develop an add-on to the Stability Mapping program (StabMap) to incorporate areal ARBS calculations. The program will utilize the currently available geologic database from SurvCADD mine models to generate an area wide CMRR grid. The program will also use LaModel outputs to calculate overburden and multiple seam stresses which will be combined to simulate an “in situ” mining condition and convert the “in situ” stress to an equivalent areal “pseudo-depth” grid. These grids will serve as inputs in areal ARBS calculations. Finally, a resulting grid consisting of ARBS intensity values will be created which can be overlaid on a mine map for better understanding of support requirements over different parts of the mine.

Chapter 2

Literature Review

2.1 General

Over the years, many tools have been developed to assist the mine engineer in assessing the stability of a mine opening by understanding the geologic characteristics of the roof rocks and to predict their behavior when subjected to induced stresses. The advancement in computer technology has improved the compatibility of these stand-alone tools so that they can be used in association with each other. Another recent development in mine evaluation technology is the introduction of geologic mapping software, such as SurvCADD, which allow the user to develop a complete geologic model of the mine property.

Tools like Coal Mine Roof Rating (CMRR) have been widely used in the mining industry to mechanistically quantify the quality of rocks. The simplicity and effectiveness of Coal Mine Roof Rating (CMRR) make it a versatile input as a geotechnical feature within different ground control tools. Previous works have shown the association of CMRR in creating more thorough stability maps (Riefenberg, 1994). A more recently developed computer program has shown great promise in calculating area wide CMRR by utilizing geologic information from SurvCADD mine models (Petrovich, 2006). Similarly, various numerical modelling techniques, like LaModel program, have been developed to help mine engineers and researchers to obtain a better understanding of more intricate mechanical state of underground structures under complex geometric and geologic conditions. Since its introduction, LaModel is being used intensively in the mining industry and has been upgraded to increase the accuracy of the calculations of seam stresses and displacements, to model multiple seams, multiple mining steps and a variable surface topography. These applications

have proved to be helpful in studying underground conditions and can be used to estimate appropriate roof support requirements to prevent roof fall related injuries.

As mentioned earlier, the design of roof bolt systems has previously lacked a scientific basis which led to the development of ARBS to analyze the performance of roof bolt systems (Mark et al., 2001). This tool performs particularly well for a given CMRR and depth of cover but the calculations must be adjusted to include cases of more complex roof quality and stress conditions. However, incorporating more detailed results as obtained from programs like areal CMRR and LaModel into ARBS calculations will help in providing significantly better roof reinforcement and a safer work environment. Previously, separate studies have shown the effectiveness of the Stability Mapping program (StabMap) in utilizing both these tools to generate a “Stability Factor” and a Roof Fall Risk Index (RFRI) system for better understanding of the unstable areas of the mine (Wang and Heasley, 2005) (Peng et al., 2006). The creation of the areal tool as an add-on to StabMap will provide an easy, quick and comprehensive package to the mine engineer to design potentially more effective roof bolt systems by using the available geologic and geo-mechanical data.

2.2 Coal Mine Roof Rating (CMRR)

In civil engineering and hard rock mining, systems such as, Rock Quality Designation (RQD), Rock Mass Rating (RMR), Q system, and others were powerful enough tools to provide for an engineering quantification of the geology for stability design of hard-rock tunnel design and other underground facilities, but they did not consider the layered sedimentary geology and geologic structures specific to coal measuring rocks (Molinda and Mark, 1996).

To facilitate an easy and understandable communication between geologists and engineers, it was necessary to create a tool which can combine geologic and quantitative description, and provide an easy interpretation of the engineering strength of the mine roof. Many attempts had been made to develop a coal mine roof specific classification system, but none had been entirely fruitful. While

some of them took only drill core information others were developed for only local classes of mine roof. The USBM developed CMRR by identifying geotechnical roof parameters and quantifying their influence on the roof strength to a single value (Molinda and Mark, 1994). The CMRR mostly focused on the discontinuities, such as bedding planes, slickensides, and joints etc., which weaken the roof (Figure 2.1).

Figure 2.1: Components of USBM Coal Mine Roof Rating (after Molinda and Mark, 1994)

2.2.1 Components of CMRR

2.2.1.1 Discontinuities

A discontinuity can be any feature such as a fault, fracture, bedding plane, or joint that may weaken the rock. The ability of a discontinuity surface to resist shearing movement is a function of the cohesion and roughness.

Cohesion is the measure of the ability of two surfaces to resist sliding when no normal force is being applied. The value of cohesion varies highly in a coal mine roof because of different types of

rock. In CMRR field tests, the cohesion is measured by a splitting test with a 3.5 in mason chisel and the number of blows required to split a rock along the bedding planes.

The roughness is visually determined by inspecting the discontinuity and assigning it a description of jagged, wavy, or planar (See Figure 2.2). The roughness can greatly affect the shear strength of the surface, assisted by the cohesion. If the cohesion is very high, then the roughness will come into play. On the other hand, if the cohesion is very low, the surface will easily separate and roughness will not matter in this case (Molinda and Mark, 1994).

Figure 2.2: Visual classification for roughness (after Molinda and Mark, 1994)

2.2.1.2 Discontinuity Intensity

Along with cohesion and roughness, the “intensity” of the discontinuity set is also very important which is determined by measuring the spacing and the persistence of the discontinuities within a unit. The spacing is measured by finding the distance between discontinuities within a discontinuity set measured within a given length of roof. The persistence of a discontinuity set is the measure of the size or areal extent of the discontinuity. A discontinuity set with very wide spacing that does not cover much area has little consequence to the mine roof, whereas a discontinuity set that is either closely spaced or covers a wide area can cause severe problems regarding roof control (Molinda and Mark, 1994).

2.2.1.3 Compressive Strength

The compressive strength determines the ability of the rock unit to provide anchorage to a roof bolt and the ability to stop fractures from forming and propagating within the unit. In CMRR tests, the compressive strength is estimated by striking the rock with a simple 3 lb. ball-peen hammer and inspecting the nature of the indentation made by the blow. The shape of the indentation is the important aspect to be recorded, not the magnitude. The indentation can be classified in one of five ways; from having the hammer rebound and not leave a mark to the rock molding and crumbling under the force of the blow (See Figure 2.3) (Molinda and Mark, 1994).

Figure 2.3: Ball peen hammer impact test (after Molinda and Mark, 1994)

2.2.1.4 Moisture Sensitivity

The moisture sensitivity of the mine roof rocks reflects the ability of the rock to disintegrate in the presence of groundwater inflow or humid mine air. In CMRR field tests, the moisture sensitivity is determined by visual estimation as well as an optional water immersion testing over a 24-hour period. Once the moisture sensitivity is determined a moisture adjustment to the CMRR is assigned accordingly (Molinda and Mark, 1994).

2.2.1.5 Non-Unit Information

The amount of groundwater greatly affects the strength of the roof rock as well as the strength of overlying bed above the highest unit in the bolting horizon. These parameters are considered for the overall mine area. (Molinda and Mark, 1994).

2.2.2 CMRR calculations

To calculate the CMRR, the roof strata is divided into individual units and a field datasheet (Figure 2.4) is filled for the above-mentioned parameters and then suitable ratings are assigned and adjustments are made by referring to the look-up tables provided with the data sheet (See Table 2.1 for example) (Molinda and Mark, 1996). The tables provide ratings and adjustments for: cohesion-roughness, spacing-persistence, strength of the unit, moisture sensitivity of the rock, and multiple discontinuity units. The final step in calculating CMRR is the summation of the lowest discontinuity rating for a multiple discontinuity adjustment, a strength adjustment, and a moisture adjustment. The procedure is repeated for individual units and final ratings are entered in the final calculation sheet to obtain the CMRR (Figure 2.5). (Please see the NIOSH IC 9387 for a complete description of calculating a CMRR.)

Table 2.1: Cohesion-Roughness rating (after Molinda and Mark, 1994)

Roughness	(1) Strong Cohesion	(2) Moderate Cohesion	(3) Weak Cohesion	(4) Slickensided
Jagged	35	29	24	10
Wavy	35	27	20	10
Planar	35	25	16	10

DATE _____ MINE _____ LOCATION _____ PAGE _____ OF _____ CMRR _____

TYPE OF EXPOSURE _____ NAME _____

UNIT						UNIT DISCONTINUITIES							
Unit No.	Unit Thickness	Strip Log	Description	Strength	Moisture Sensitivity	Disco. I.D.	Description	Cohesion	Roughness	Spacing	Persistence Lateral/Vert	Orientation Strike Dip	
3						A.							
						B.							
						C.							
	CONTACT												
2						A.							
						B.							
						C.							
	CONTACT												
1						A.							
						B.							
						C.							
<p>Rebounds >100 MPa (15,000 psi) Pits 100-50 MPa (15,000 - 8,000 psi) Dents 55-21 MPa (8,000 - 3,000 psi) Craters 21-7 MPa (3,000 - 1,000 psi) Molds <7 MPa (1,000 psi)</p>	1	Rebounds	Not Sensitive	1	Strong (>7)**	Jagged	>1.8 m (6 ft)	0-0.9 m (0-3 ft)	N.	Horiz.			
	2	Pits	Slightly Sensitive	2	Moderate (4-7)	Wavy	0.6-1.8 m (2-6 ft)	0.9-3 m (3-10 ft)	NE.	Subhoriz.			
	3	Dents	Moderately Sensitive	3	Weak (1-3)	Planar	20-60 cm (8-24 in)	3-9 m (10-30 ft)	E.	45°			
	4	Craters	Severely Sensitive	4	Slacken-sided (0)		6-20 cm (2.5-8 in)	>9 m (30 ft)	SE.	Subvert.			
	5	Molds		5			<6 cm (2.5 in)		S.	Vert.			
Groundwater (inflow/10 m (33 ft) of entry length) (Circle) L/min (gal/min)				Describe condition in vicinity of fall (circle one)		** Hammer blows necessary to split bedding with 9-cm (3.5-in) chisel. COMMENTS: (Roof Support, etc.)							
Dry 0 1 Heavy Drip 10-50 (2.7-12.2) 4 Damp 0-5 (0-1.3) 2 Flowing >50 (13.2) 5 Light Drip 5-10 (1.3-2.7) 3				1. Good 3. Heavy 2. Scaly 4. Failed									

Figure 2.4: CMRR field data sheet (after Molinda and Mark, 1994)

Mine Name _____ Date _____
Location _____ Data Collected by _____

$$\begin{array}{c} + \\ \boxed{} \\ + \\ \boxed{} \\ + \\ \boxed{} \\ + \\ \boxed{} \\ \hline \boxed{} = CMRR \end{array}$$

11

2.2.3 CMRR Program

Owing to the popularity of CMRR, the National Institute for Occupational Safety and Hazard (NIOSH) developed a simple computer program to facilitate the data collection and do the calculations for the CMRR. The program allows the users to calculate CMRR from in situ observation or drill core inputs (Mark et al., 2002). This allows the user to easily vary the parameters to see their effect on CMRR. The data must be entered manually for individual points either by using the drop-down menus or directly. One important feature of this program is that it consists of a built-in interface with AutoCAD. Data from numerous points, along with their coordinates, are entered in a single file. The program creates a “. CMR" file generated by the program which can be exported to AutoCAD, with the calculated CMRR and the coordinates. A CMRR layer can be created in AutoCAD for any further use. The forms (Figures 2.6 and 2.7) in the computer program are designed similar to the original field data sheet, as shown in Figures 2.2.

The screenshot displays the 'Parameters' dialog box of the CMRR program. A secondary window titled 'Underground Exposure Sheet unit: 1' is overlaid on top. This window contains the following fields and controls:

- Additional comments for unit:** COAL
- Strength index:** A dropdown menu with '1.0 Rebounds' selected.
- Number of discontinuities:** A numeric input field set to '2'.
- Discontinuity details:** A table with columns for 'Discontinuity', 'Roughness', 'Spacing', 'Persistence', and 'Description'.

Discontinuity	Roughness	Spacing	Persistence	Description	
1.0 Rebounds	1.0 Jagged	1.0 >6 ft	1.0 0-3 ft		
Set 2	1.0 Strong	1.0 Jagged	1.0 >6 ft	1.0 0-3 ft	
Set 3					
- Moisture sensitivity index:** A dropdown menu with '1. Not Sensitive' selected.

At the bottom of the 'Underground Exposure Sheet unit: 1' window are buttons for 'Copy dialog image to clipboard', 'Print dialog', 'Help', 'Cancel', and 'OK'. The main 'Parameters' dialog box at the bottom has buttons for 'Copy dialog image to clipboard', 'CMRR report', 'Plot roof layers', 'Help', 'Cancel', and 'OK'.

Figure 2.6: Underground information form, CMRR program (Mark et al., 2002)

Parameters
Drill Core Sheet unit: 1

Additional comments for unit: COAL

Axial PLT

Number	Depth (ft)	Is(50) (psi)	UCS (psi)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0

Diametral PLT

Number	Depth (ft)	Is(50) (psi)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0

Axial test parameters

☐ Use table average UCS (psi)

☒ User defined UCS (psi)

Diametral test parameters

☐ Use table average Is(50) (psi)

☒ User defined Is(50) (psi)

☐ No diametral PLT data available

Moisture sensitivity index

1. Not Sensitive

Fracture intensity

☒ RQD (%)

☐ Fracture spacing (in)

☐ No fractures observed

Copy dialog image to clipboard Print dialog

Help Cancel OK

Figure 2.7: Drill core information form, CMRR program (Mark et al., 2002)

2.2.4 Areal CMRR calculation

The CMRR program developed by NIOSH is a successful tool in calculating CMRR and is widely used in the mining industry. But despite its success, it suffers from a few limitations. As stated above, both observational and drill core geologic data necessary for the calculation must be entered manually for individual points, and the CMRR calculations must be individually processed at those individual points. When point observations are used for the CMRR calculations, numerous points need to be analyzed for the process. Over a large mine area, this can be quite tedious and time consuming work.

To overcome the limitation of CMRR being location-specific, a computer program was developed by Petrovich (2006) which combines the CMRR calculations with the geologic mapping software SurvCADD to calculate an area-wide CMRR. The program uses the SurvCADD geologic

model as a source of input for the parameters required to calculate CMRR. As a mineral deposit is explored, the boreholes and drill cores provide tremendous amounts of data regarding the geology of the immediate roof of the deposit. As a mine is developed, additional data can be, and often are, added to the geologic database through channel samples and other underground observations. With the availability of such a large pre-made geologic database, the calculation of CMRR becomes quick and easy with most of the required parameters already present in the mine's geologic model. The program conveniently takes advantage of the data already present in the geologic model to optimize the CMRR calculation. The program also takes input from both underground observations and core data from boreholes and drill core logs. Unit ratings and weightings to the parameters are provided as per the traditional tables (Molinda and Mark, 1994) hardcoded into the program. The difficulty with using these tables directly is that they can only be referenced for round numbers within the table and not fractional values in between. The program allows the full range of input within the limits of a factor and successfully interpolates a value based on the known data and gives a discreet input. The program follows the user-friendly design of the previous CMRR program (See Figures 2.6-2.7). The input forms are simple and easy to understand for both general information and rating tables for data entry and CMRR calculations (See Figures 2.8-2.12).

- **General information form**

The main form for the areal CMRR calculations is the “***General Information form***” (See Figure 2.8). This form allows the user to use the “***Type of Data***” which can be either “***Underground Observations***” or “***Core Hole Data***” for a maximum of 5 “***Number of Units***”. For each unit, the user may choose to either input a single “***Thickness (ft)***” value or use a grid of thickness values into the program. After the thickness data is entered the user may either enter a known “***Unit Rating***” in the edit box or provide additional information using the “***Details***” button which brings up either “***Underground Observation Data***” form or a “***Core Data***” form.

General Information

File Name: CMRR-AN [Open...] [Save] [Save As...] [Cancel] [Next...]

Type of Data: ☒ Underground Observation ☐ Core Hole Data

Number of Units: 4

Unit	Thickness (ft)	Thickness From File	Thickness Grid File	Unit Rating
Unit5	0	☐ File		0
Unit4	0	☒ File	C:\Users\Gunn\\Desktop\Bowie-Al	58
Unit3	0	☒ File	C:\Users\Gunn\\Desktop\Bowie-Al	34
Unit2	0	☒ File	C:\Users\Gunn\\Desktop\Bowie-Al	39
Unit1	0	☒ File	C:\Users\Gunn\\Desktop\Bowie-Al	47

Figure 2.8: General information form- CMRR program (After Petrovich, 2006)

- **Underground Observation Form**

The “*Underground Observation*” form allows the user to input the information necessary to calculate a unit rating based on observational data (See Figure 2.9). The first step is to choose to manually enter an individual “*Strength Index*” between 1 and 5 or from one of the pre-defined values from the pull-down menu or a grid “*File*” of strength values. The next step is to select the “*Number of Discontinuities*” that are present within the unit. Once the number of discontinuities is entered, the details of all the discontinuity “*Sets*” data has to be provided. The third step is to input information for “*Moisture Sensitivity Index*” and for strength of “*Contact at Top of the Unit*”. For the moisture sensitivity index, the user may enter a number between 1 and 4 or select one of the pre-defined values from the pull-down menu. The contact strength can be defined as “*Weak*” or “*Strong*”.

Underground Observation Data

Strength Index: 3.5

Strength Grid File: ☐ File Grid...

Discontinuities: Number of Discontinuities: 1 Sets...

Moisture Sensitivity Index: 1.0 Not Sensitive

Contact at Top of the Unit: ☒ Strong ☐ Weak

Cancel OK

Figure 2.9: Underground observation form- CMRR program (After Petrovich, 2006)

- **Discontinuities form**

Once the “*Sets*” button is clicked, the details of the discontinuities are entered in the discontinuities form (See Figure 2.10). This form allows the user to enter “*Cohesion*, *Roughness*, *Spacing*, and *Persistence*” data for each set from the pull-down menu.

Discontinuities

	Cohesion	Roughness	Spacing	Persistence
Set 1	1.0	1.5 Jagged - Wavy	4.5	1.5
Set 2	2.5 Moderate	1.0 Jagged	2.5	1.0 0 - 3 ft
Set 3	2.5 Moderate	2.5 Wavy - Planar	2.0 2 - 6 ft	2.5

Cancel OK

Figure 2.10: Discontinuity form – CMRR program (After Petrovich, 2006)

- **Core Data form**

If the “*Core Hole Data*” is chosen in the General Information Form (See Figure 2.8), the “*Details*” button brings up the “*Core Data*” form (See Figure 2.11). In this form, the user can enter the diametral strength information, if available, by entering single average point load test strength (both single value or grid file), “*Is(50) psi*” or “*No Diametral Available*” if absent. The next step is to choose which type of “*Fracture Information*”, for which both single value or a grid file can be entered for “*RQD %*”, “*Discontinuity Spacing (in)*” or “*No Fractures*”. Furthermore, both single value or a grid value can be used for “*Is(50)*” or a “*UCS*” can be entered in the “*Axial Test Information*”. The strength of “*Contact at Top of Unit*” and the “*Moisture Sensitivity Index*” is also entered before proceeding to the final form.

The screenshot shows the 'Core Data' form with the following sections and controls:

- Diametral Test Information:**
 - ☒ Is(50) (psi) [Text box: 0] ☐ File [Grid File text box] [Grid... button]
 - ☐ No Diametral Available
- Fracture Information:**
 - ☒ RQD % [Text box: 0] ☐ File [RQD% Grid File text box] [Grid... button]
 - ☐ Discontinuity Spacing (in) [Text box: 0] ☐ File [Discontinuity Spacing Grid File text box] [Grid... button]
 - ☐ No Fractures
- Axial Test Information:**
 - ☒ Is(50) (psi) [Text box: 0] ☐ File [Axial Is50 Grid File text box] [Grid... button]
 - ☐ UCS (psi) [Text box: 0] ☐ File [Axial UCS Grid File text box] [Grid... button]
- Contact at Top of the Unit:**
 - ☒ Strong ☐ Weak
- Moisture Sensitivity Index:**
 - 1.0 Not Sensitive (dropdown menu)
- Buttons:** [OK] [Cancel]

Figure 2.11: Core data form- CMRR program (After Petrovich, 2006)

- **Final Data Parameters form**

Once all the data has been entered and the “**OK**” button is clicked, the program returns to the General Information form shown in Figure 2.8. As the “**Next**” button is clicked, the “**Final Data Parameters**” form is brought up (See Figure 2.12). In this form, the non-unit information for “**Ground Water Adjustment**” and “**Surcharge Adjustment**”. values can be entered by using corresponding single average value, a grid of values or by using pull-down menus. The next step is to enter the “**Bolt Length**”. The “**Keep Unit Grid Files**” box option will only be active if the unit grid files have been calculated in the previous steps. The areal CMRR calculation is completed by clicking on the “**Finish**” button and either a single CMRR value will be displayed in the “**Final CMRR**” box, or a grid of CMRR values will be sent to the directory in which the current CMRR program is being run.

Final Data Parameters

Ground Water Adjustment: 2.0 Damp

Ground Water Grid File: ☐ File Grid...

Surcharge Adjustment: 1.0 Unit above bolted interval is equal in strength to the bolted ui

Bolt Length(ft): 6

Keep Unit Grid Files: ☐ Yes

Final CMRR: 0

<--- Back Cancel Finish OK

Figure 2.12: Final data parameters form – CMRR program (After Petrovich, 2006)

2.3 Analysis of Roof Bolt Systems (ARBS)

To provide a scientific basis to the design of the roof bolt systems, NIOSH conducted a statistical study over 37 mines distributed across the U.S, collecting nearly 100 case histories of different roof fall categories totalling more than 10000 ft of drivage. The outcome of the study was a variable, ARBS, which is essentially the required bolt support intensity to support the mine roof depending on the roof quality, stress and mine geometry.

2.3.1 ARBS parameters

The ARBS value acts as a guideline to suggest the required bolt length, capacity, and pattern needed to successfully support the mine roof over an entry or an intersection. The critical input values to the ARBS calculation include: the roof quality (CMRR), depth of cover (stress), and the intersection span.

2.3.1.1 Effect of Roof Quality (CMRR)

The performance of roof bolts depends on the quality of the roof that it supports. The study by Mark et al. (2001) showed that the mines with weaker roof in high stress environments were more likely to encounter roof falls even with high support density; while on the other hand, mines with strong roofs with low stress environment do not fail even with less support density. In the ARBS calculation, the CMRR was used as the tool to describe the roof quality. It was observed that, for the mines with a CMRR less than 50, the failure rate was 64%, i.e., 29 cases were categorized under the failure category while only 16 were categorized successes. On the other hand, for mines with a CMRR greater than 50, the failure rate was only 14% (see Figure 2.13), (Mark et al., 2001).

Figure 2.13: Roof fall rates for different CMRR values (Mark et al., 2001)

2.3.1.2 Effect of Stress (depth of cover)

The bolting effectiveness depends on the the rock properties as well as the surrounding stress regime. The same roof bed acts differently and may require different support mechanisms under different stress environments. While the pillars take on much of the vertical stress, the horizontal stress has a more direct effect on the mine roof. Since the direct measurment of horizontal stress is not possible, it is usually correlated to the depth of the cover (Mark et al., 2001) (Mark and Mucho, 1994).

The stress level plays an important role in deciding the type of support mechanism required for a type of the roof. The ARBS calculation performs best under beam building conditions where the rock is weaker or the stress is higher rather than skin control or suspension mechanisms. The level of stress acting on the roof directly impacts the transition between these mechanisms.

Figure 2.14: Skin control (Mark, 2000)

Figure 2.15: Suspension (Mark, 2000)

Figure 2.16: Beam Building (Mark, 2000)

Figure 2.17: Supplemental support (Mark, 2000)

It was found that roof falls were rare in the zones with a strong roof/or low stress regime where roof bolts work by suspension or skin control with a stronger self-supporting roof or layer above the weak roof or a shallow depth.

2.3.1.3 Effect of Entry Design (Intersection Span)

In the study, it was observed that almost 70% of the roof falls occur at the intersections even though they cover only 20-25% of the total drivage (Molinda et. al, 1998). The effect of rock quality and the ratio of horizontal to vertical stress play an important role in the stability of the intersections. The intersection span used in ARBS is the average of the sum of the diagonal measurement across the intersection.

Figure 2.18: Roof fall cases vs Intersection Span (Molinda et al., 2000)

2.3.2 ARBS Calculations

For the collected case histories, the results of the study predicted 76% of the successful and failed cases which is significant as compared to the complete absence of any previous scientific basis. The result of the study was in the form of an equation that cumulates the effect of geology, stress and intersection span, which is given as (Mark et al., 2001):

$$ARBS = (SF)[(0.3*(I_{SG} - I_s)) + (5.7 \log_{10} H) - (0.35*CMRR)) + 6.5] \quad (2.1)$$

Where:

ARBS = Suggested value of ARBS for given CMRR and depth of cover

SF = the Stability Factor (1.2 recommended)

I_{SG} = Suggested intersection span (ft.)

I_S = Actual intersection span (ft.)

H = Depth of cover (ft.)

CMRR = Coal Mine Roof Rating

While ARBS provides the required roof bolt density to support an area, its significance can be further extended to the design roof bolt systems. The calculated ARBS value is used to determine the roof bolt characteristics (Mark et al., 2001)

$$ARBS = \frac{(L_b)(N_b)(C)}{(S_b)(W_e)} \quad (2.2)$$

Where the roof bolt parameters are:

L_b = Length of the bolt (ft.)

N_b = Number of bolts per row

C = Bolt capacity (kips)

S_b = Spacing between rows of bolts (ft.)

W_e = Entry width (ft.)

The value for ARBS is typically calculated manually at individual points and repeated at numerous locations of the mine. The ARBS calculations over a wide area would be a time-consuming process. Further, ARBS does not consider multiple seam stress interactions or abutment stresses generated by longwall or retreat mining. It seems reasonable that developing a method to incorporate the areal variation in CMRR and multiple-seam stresses into the ARBS calculation would improve the accuracy and utility of the ARBS in roof bolt design. Further, while, ARBS provides engineers with a

bolt intensity value, it does little to suggest the exact type or length of bolt which will be suitable enough for holding the roof. Once a certain required ARBS value has been obtained, it should be possible to suggest diameter, or grade of steel to meet the requirement. A mechanism for suggesting the appropriate type of bolt will be an innovative and useful add-on to the ARBS program.

2.4 LaModel

The LaModel program (pre-processor, LamPre, and post-processor, LamPlt) was the first of the displacement discontinuity programs to be developed in the more modern object oriented, visual programming environments. To increase the accuracy of the stress and displacement calculations for stratified rock masses, laminations were added to the overburden in the displacement discontinuity method to create the LaModel program (Heasley, 1998). In addition, the ability to input a variable topography was introduced with the original LaModel program.

Figure 2.19: Schematic of laminated overburden (after Heasley, 1998)

In comparison to MULSIM/NL, LaModel implemented the same in-seam material models such as linear-elastic, strain-softening, elastic-plastic, strain hardening, bilinear hardening and linear elastic gob (Heasley, 1998 and Zipf, 1992). However, LaModel also added much more advanced features such as:

- A Laminated overburden model instead of a homogeneous elastic mass overburden
- Stress and displacement analysis for broad areas
- Faster definition of seams grids and mining steps with an easy-to-use preprocessor
- Subsidence prediction
- Topography effects
- Energy calculations
- Graphic output by the post-processor LamPlt.

The typical output for a multiple-seam LaModel simulation includes: seam convergence, total vertical stress, surface effect stress, multiple seam stress and overburden stress. These basic outputs provide most of the necessary stress information for a mine stability analysis.

2.5 Stability Mapping

In order to ensure stability in a mine opening, a mining engineer needs to consider the geology, the stress conditions around the opening and the roof support. To understand the effect of these factors over the life of the mine opening, various tools and techniques have been developed over the years. In order to evaluate the geology conditions, geologic “hazard” maps were created demarcating the mine areas with poor or weak geology (Stankus et al., 2001; Newman et al., 2001; Reifenberg, 1994). Figure 2.9 shows an example of an earlier version of a hazard or stability map.

Figure 2.20: Hazard Map (after Riefenberg, 1994)

These maps assisted engineers to make modifications in the mine plan which included changing the pillar designs, or increasing the roof support in weaker mine areas. Historically, these maps included the geologic or geophysical characteristics of the deposit such as rock strength, discontinuities etc. and did not consider the stress influences like overburden stress, multiple-seam stresses, etc. or the geometric influences such as complex pillar plans or multiple seams. In situations where the stresses or geometries had a significant influence, the pure geologic hazard map did not provide an accurate picture of the stability of the mine opening.

To fully analyze the stability of a mine, it is essential to combine both geologic and mechanical influences. With the goal of incorporating both geology and stress, an Integrated Stability Mapping System was developed (Wang and Heasley, 2005). This system takes AutoCAD/SurvCADD as a mapping platform for gathering all the geologic characteristics and then tightly integrates with LaModel for determining stress influences (Wang and Heasley, 2005). The geologic data can be

collected from a geologic model in SurvCADD. The modules in the stability mapping system allow easy transfer of stress analysis outputs from a LaModel analysis. With the help of independent modules, executable in AutoCAD, stability mapping provides a menu and command system for developing stability maps.

2.6 AutoCAD and Customization

AutoCAD is the most widely used design software because it allows the flexibility to extend from a general drawing package to professional design package for industry specific fields. AutoCAD provides various options to users to customize its applicability by accessing the embedded languages or advanced extension methods of its subroutines. Some of the methods for AutoCAD customization include:

- DIESEL – String Expression Language
- Command Scripts
- AutoLISP
- ObjectARX -- AutoCAD Runtime eXtension
- AutoCAD VBA
- Plug-in Applications

All these customization methods have their own capabilities and limitations. Therefore, the best approach for developing an application depends on the demands of the project. In this research, ObjectARX is used as the preferable method because applications developed in this environment typically run faster than other methods and the programming environment is very flexible. An ObjectARX application, is a Dynamic Link Library (DLL) that shares AutoCAD's address space and makes calls directly to AutoCAD. However, since ObjectARX applications share the same memory address space with AutoCAD, AutoCAD may crash if the ObjectARX application does not handle exceptions properly.

2.6.1 ObjectARX Programming

ObjectARX (AutoCAD Runtime eXtension) is a C++ Application Programming Interface (API) environment, developed and provided by Autodesk, which provides an object-oriented API within the AutoCAD system. By using ObjectARX libraries, developers can directly access AutoCAD database structures, the graphics system, define native commands and get notified of specific AutoCAD events. ObjectARX allows applications to create intelligent design objects as custom entities, which become part of the AutoCAD database. These custom entities are virtually indistinguishable from built-in AutoCAD entities such as points, lines etc. In addition, the new classes added in the ObjectARX environment can be exported for use by other programs further extending their applicability.

Applications created (with an extension “. *arx*”) by using the ObjecARX SDK are considered by AutoCAD an extension of itself. Using this SDK, one can not only customize AutoCAD, but extend it to where AutoCAD becomes just the base for a new application or product. Autodesk has led the way by highly advanced products such as Mechanical and Architectural Desktop built on top of AutoCAD using ObjectARX. Thus, ObjectARX is rapidly becoming the first choice for serious application development in the AutoCAD environment.

Chapter 3

Design of areal ARBS

3.1 General

The areal ARBS program takes area based CMRR and stress inputs in the calculations. The geologic information for CMRR calculations can come from different number of sources with different formats. Usually, this data is stored in a grid format. In addition, the stress data used in the calculations are also required to be stored in a certain format. To perform areal ARBS calculations, it is essential that the continuity in the data format is maintained throughout the program. In this research, SurvCADD and LaModel were justifiably chosen as the primary source of input data as the grid format is compatible with both these tools and StabMap environment. This chapter discusses the data format, data requirements and software which were used to design the program.

3.2: Data Format:

To perform ARBS calculations using the existing SurvCADD geologic database, it is essential that all the areal inputs and outputs should have the same format compatible with the mapping software SurvCADD. Because of this reasoning, the SurvCADD grid format (“`. grd`” extension) was chosen for storing the ARBS data. The advantage of having the same native SurvCADD grid format is that the data grids can be shared between the different modules involved in the areal ARBS calculations, StabMap and AutoCAD/SurvCADD.

A grid is a 3-Dimensional matrix that stores x, y coordinates of a point with a z value consisting of the geologic (or any) data for that point. When a grid is created, the grid origin and dimensions are specified. The area is then divided into grid elements per the dimensions of the grids (x and y spacing). The z value can be different parameters for different applications, such as, layer thickness, material density, etc.

A typical grid file (*.grid) follows this design:

```
19400.0000
25000.0000
27000.0000
32600.0000
760
760
7.991383521
7.762025639
....
```

The first four lines of the grid file contains the information regarding the location coordinates of the base points of the grid. These values are:

- The first line is the Northing, or Y, coordinate of the lower left corner of the grid
- The second line is the Easting, or X, coordinate of the lower left corner of the grid
- The third line is the Northing, or Y, coordinate of the upper right corner of the grid
- The fourth line is the Easting, or X, coordinate of the upper right corner of the grid

The next two lines give the number of grid elements in the X and Y directions respectively. The program uses this information to draw the grids and to compare with the other grid files to ensure that the files are located at the same base point and have the same dimensions. The next lines are the Z values of the grid elements starting from the lower left and moving first up the column and then from left to right, and ending at the upper right point.

3.3 Data Requirements

For the geologic part of the ARBS input, the SurvCADD program provides the basic information such as layer thickness, strength, chemical composition, etc. from a variety of sources such as surface drill holes, underground samples or observations. It is essential to ensure that the data is compiled and stored, in the format which is compatible with StabMap.

For the stress representation in the area-wide ARBS, the output of a LaModel analysis is intended as the key input. Therefore, it is highly essential to prepare an accurate topographic model with the same grid definition used for creating CMRR. The model parameters must be carefully entered and the results must be consistent with the observational or experimental study of the mine site. Any inconsistency must be addressed before using them for ARBS input.

In addition, since StabMap directly extracts input data from AutoCAD files, all the geologic contours and structure features must be represented as native entities inside the AutoCAD maps. These entities may be points, lines or polylines depending on the nature of the features. It is also necessary to examine the integrity of these entities before applying automatic gridding. For instance, when applying gridding on the topographic contour lines, these contours are required to be polylines with proper elevations and without intersections and for using StabMap grid modules the polylines/polygons must be closed before gridding.

3.4 Grid Read and Write

Because the program allows input from a various number of sources, it is highly essential that the grid being read is checked for validity. The program performs number of checks before proceeding to calculations. The first checkpoint is to ensure that each grid is of the same size and location. The second error check is to analyze the data values being read into the program. Various components of CMRR have upper and lower limits that cannot be breached for the program to run properly. As an example, if the strong bed has given a thickness of 1.5 ft. it cannot have a strong bed difference of 4 as it will be out of lower limit bound for that factor. Each point that is read from the grid is compared to the bounds for the type of factor to which the data are going to be applied. The third error check is to make sure that there are not any values which are not appropriate for the given grid. Since the data value for the ARBS calculation all consist of numeric values, the grid file is checked for any non-numeric or null values.

3.5 Program Creation

The computer program for the ARBS calculations had to be compatible with AutoCAD/SurvCADD and it had to be able to handle very large amounts of data. Therefore, the application was built using Microsoft Visual C++ and was programmed using ObjectARX (an AutoCAD runtime extension). ObjectARX allows one to program in Visual C++ with an application developer's toolkit from Autodesk to create programs that will load and run in the AutoCAD environment. To create a user interface for the program, numerous classes are available, which make it easy to create forms, drop down menus, buttons, etc. as typical in a windows program, in ObjectARX.

Chapter 4

Implementation of area wide ARBS

4.1 General

One important aspect of developing the areal ARBS tools was to implement efficient calculations while maintaining the user-friendly design of the conventional ARBS program developed by NIOSH. Hence, similar kinds of forms have been programmed in the areal ARBS module in StabMap. Once the input forms are activated, the user can easily proceed through the self-explanatory forms to the calculations and output. A detailed walkthrough for the procedure is provided in this chapter.

4.2 User Interface

4.2.1 Loading Stability Mapping Application

The ObjectARX applications are loaded from the “*load application*” command from the Tools menu in the AutoCAD menu bar or from the command line (command: “*appload*”). After the command is entered, a window appears where “*StabilityMapping.arx*” can be browsed, selected and loaded (See Figure 4.1). After the application is loaded, a new pull down menu item titled “*Stability_Mapping*” appears on the AutoCAD menu bar. To lead to the calculations, two items were added to the existing StabMap menu system for performing an area-based CMRR and ARBS calculations (Figure 4.2).

Figure 4.1: Loading StabMap in AutoCAD

Figure 4.2: StabMap menu system

4.2.2 Areal ARBS module

The interface for the forms was kept simple and self-explanatory to avoid any confusion with inputs and other functions within the program. The continuity of user interface from the StabMap is maintained and similar forms were programmed for ARBS input and output. Before proceeding to the ARBS calculations, it is recommended to have roof information and stress analysis result compiled as grids. The areal ARBS calculations consist of five major steps:

- CMRR grid generation
- Pseudo-depth grid generation
- Intersection span generation
- Areal ARBS calculation and grid generation
- Plotting ARBS grid
- **CMRR grid generation**

As a part of this research, the previous work done by Petrovich (2006) on a geostatistical tool for area wide CMRR calculation was extended and the tool was updated to run in the latest versions of Microsoft Visual C++ and AutoCAD libraries and was integrated within StabMap. The “***Coal Mine Roof Rating (CMRR)***” module can be accessed through the “***Stability Mapping***” menu item or directly from the command line (command: “***smap_cmrr***”). The module lets the user read in geologic data from the SurvCADD geologic database to calculate CMRR over a wide area.

Once the CMRR module is clicked, the general information form pops up and geologic information can be entered by going through the forms explained in Chapter 2 (See Figures 2.8-2.12). In the absence of any detailed information on certain parameters, the module allows the user to create a grid and populate it with a single value over all the grid points. Once all the needed information is entered, specific units are identified and ratings are provided to individual units. These ratings are

calculated per the traditional weighting tables and final adjustments are made for contact, groundwater and surcharge (Molinda and Mark, 1994). These calculations are carried out in a loop over each grid point and for multiple units (if any) to obtain a CMRR value for each grid point (See Figure 4.3). These CMRR values are stored in a grid file which serves as the CMRR input for the ARBS calculations.

Figure 4.3: Flowsheet to Generate CMRR Grid

- **Pseudo-depth grid generation**

In ARBS, the effect of horizontal stress on the coal seam is correlated to the depth of cover (Mark et al., 2001). Because the horizontal stress intensifies with factors such as varying topography, multiple-seam mining, abutment stress, etc. the translation of depth to stress may not always be an appropriate representation. In addition, the effect of retreat mining was also omitted from the ARBS study. To include the detailed stress effects in areal ARBS calculations, results from a LaModel analysis is imported to the StabMap platform using “*Transfer LaModal/MULSIM results*” item from the newly added “*Stability Mapping*” menu item. As the transfer window pops up, the overburden and multiple seam stresses are each saved as separate grid files (See Figure 4.4).

Figure 4.4: Transfer LaModal/MULSIM results

From the StabMap ***“Grid Utility”*** menu item, the two grids are combined using the ***“Add”*** operation (in the ***“Grid Value Manage”*** section of the window) and clicking on ***“Apply with grids”*** and selecting the both grids to obtain an “in-situ” stress grid which is saved using ***“Save As”*** button. The in-situ grid is then scaled by the stress gradient of the overburden material using the ***“Divide”*** operation (similar to ***“Add”***) to calculate a “pseudo” depth (See Figure 4.5). For multiple-seam situations, it is proposed that this pseudo-depth, which includes the multiple-seam stresses, would be a more accurate representative of stress than just the depth. This pseudo depth grid is used as the input depth for the areal ARBS calculations. The complete flow sheet for generating the pseudo-depth grid is shown in Figure 4.6.

Grid Utility

Current Grid File
 c:\users\gunnu\desktop\bowie\stabmap\upperb\arbs.grd
 Select File ...

New Grid ... Read from ... Save As ...

Grid Value Manage
 Operations: Add
 Value: 0
 Apply with Grids...
 Apply to Grid
 Statistic
 < Move Position
 < Editor
 Correlation with

Plot and Settings
 Layer: 0
 Type: Solids
 < New
 Color
 Group
 Colors ...
 < Legend
 < Preview
 < Plot

Cancel OK

grid loaded: c:\users\gunnu\desktop\bowie\stabmap\upperb\arbs.grd

Figure 4.5: Grid utility form

Figure 4.6: Flow sheet to generate pseudo-depth grid

- **Intersection span grid generation**

In most mines, the various sections of the mine, for example, mains, sub-mains, production panels, gateroads, etc., often have pillars that are specifically designed for the intended use of that section. Therefore, the intersection spans in each unique section of the mine may be different. For the area-based ARBS calculation, any difference in intersections spans between mine sections needs to be considered. The StabMap functions for working with area boundaries in AutoCAD enable the user to easily:

- 1) outline the various sections of the mine,
- 2) assign intersection span values to each section, and;
- 3) compile this data into a grid.

This grid of intersection spans would then be input to the area-based ARBS calculation for the intersection span value.

- **Areal ARBS grid generation**

The final calculation form is called from the “*Analysis of Roof Bolt Systems (ARBS)*” menu item or from the command line (command: “*smap_arbs*”). The form allows the user to enter the grid names for CMRR, pseudo depth and intersection span (See Figure 4.7). The first step is to select a location to save the “*Output File*” grid using the “*Pick a File*” button. The next step is to enter the mining factors “*Intersection Span (ft)*” and “*Entry Width (ft)*”. The user can enter a single value or by browsing and selecting a grid file after checking the “*Grid?*” box. The next step is to enter the “*Stability Factor*” (set to a default value of 1.2 as recommended by NIOSH). The final step is to enter the geology information for “*CMRR*” and “*Pseudo Depth*” and “*pcf*”. For the Intersection Span, CMRR or pseudo depth, a single value or an existing grid can be used for calculations.

Create Grid for ARBS

Output File (.grd)
 C:\Users\Gunnu\Desktop\StabMap-ARBS\arbs.grd <Pick a file

Mining Factors

Intersection Span (ft) 25 Grid? ☐ C:\Users\Gunnu\Desktop\StabMap-ARBS\arbs.grd

Entry Width (ft) 12

Design Factor
 Stability Factor 1.2

Geology

Coal Mine Roof Rating (CMRR) 45 ☒ Grid? C:\Users\Gunnu\Desktop\StabMap-ARBS\arbs.grd

Pseudo Depth (ft) 500 ☒ Grid? C:\Users\Gunnu\Desktop\StabMap-ARBS\arbs.grd

Unit Weight of Rock (pcf) 162

Cancel Build Grid OK

Figure 4.7: ARBS input form-StabMap

4.3 Areal ARBS calculations

For all the single values used during the input steps, an appropriately sized grid file is created which is populated by the entered value for each parameter. For all the parameters checked for grids, the corresponding grid files are used in the calculation. Once the inputs are received in the module, the next step is to click the **“Build Grid”** button. Once the button is clicked, calculations for ARBS values are performed (based on Equation 2.1) at every grid point and the results are stored in the output CMRR grid file. As the calculations get complete, the **“OK”** button is clicked to exit from the window. The ARBS grid can be later plotted using StabMap’s grid utilities, and overlain on the mine map. The complete flow sheet of the ARBS calculation is shown in Figure 4.8.

Figure 4.9: Flowsheet to generate ARBS grid

Chapter 5

Case Study

5.1 Introduction

To validate the accuracy of the new areal ARBS calculation, it was essential to test the program with a real-world example which would exercise most of the recently created subroutines. It was desired to validate the program for a multiple-seam scenario and to produce a comprehensive result showing the combined effect of the CMRR over a mine area with different intersection spans and a highly variable pseudo depth. In this chapter, a case study is presented that demonstrates the use of the area-wide ARBS tool within the Stability Mapping system to calculate ARBS values over an entire district of a previously active mine site.

5.2 Case Study

This case study demonstrates the use of the ARBS module within the Stability Mapping system (Wang and Heasley, 2005). The information required for calculating area wide ARBS value was obtained from previous research done to create a stability map which used an area-wide CMRR calculation (Stewart et al., 2005; Wang and Heasley, 2005; Petrovich, 2006). This information consisted of detailed lithology report, contour data for the topography and strength data for the roof rock. The lithology data was used to identify the units in the roof; the contour data was used to determine the thickness of the units and to model the topography and multiple-seam condition; strength data was used to provide ratings to the units for CMRR calculations. A LaModel analysis was performed and the stress results were imported into StabMap and converted into pseudo-depth, and as per the entry design of the mine, a constant intersection span was used (however, a varying intersection span could have been used for different sections of the mine.)

5.2.1 Background

The mine site selected for this study is located east of Paonia, in the North Fork valley of West Central CO (See Figure 5.1). For this case study, the southwest mining district was considered (See Figure 5.2). The overburden in the southwest mining district varies from a minimum of 400 ft. of cover in the south to a maximum of around 1500 ft. in the north (see Figure 5.2). Prior to the development of the mine in the B seam, a longwall mine was completed in the D seam which is located approximately 250 ft. above the B seam (see Figure 5.2).

Figure 5.1: Mine location site (from Stewart et al., 2006)

Figure 5.2: Topography over the B and D seams (Stewart et al., 2006)

Generalized Stratigraphic Column For the Bowie # 2 & 3 Mines

Figure 5.3: Generalized stratigraphic column for the Bowie mine (after Robeck, 2005)

5.2.2 Coal Mine Roof Rating Grid Generation

The general lithology was obtained from a previous work done at the mine site (Stewart et al., 2006). Once the roof units were identified from the lithology reports, four major units were identified within the immediate mine roof which effect the roof quality (See Figure 5.4). The thicknesses for these units varied depending on the location within the mining district. These details of the roof units from the most immediate to the upper most unit are:

Figure 5.4: Sandstone channels and rider interburden (Stewart et al., 2006)

- **Rider coal seam unit:** On the eastern side of the Southwest mining district, there is a rider coal seam above the main bench of the B seam. This rider is far from the main bench in the eastern corner, but gradually gets closer until it merges with the main bench of the B seam within the southwest mining district. This rider seam was separated from the B seam by interburden on the eastern side and

joined with the seam while moving to the west (see Figure 5.4). In this area, the rider coal joins the B seam and the interburden is no longer present. The grid for rider coal seam thickness was created from the provided contours using StabMap utility that allows to create a grid from contours, linear features, points, etc. (See Figure 5.5).

Figure 5.5: Rider thickness grid

- **Interburden to the rider coal seam:** The rider seam merges with the bench of the B seam as shown by the interburden thickness contours (See Figure 5.4). When the interburden is less than 2 ft. thick, it typically falls out when the underlying coal is initially mined and it is not much of a problem. When the interburden is between 2 to 6 ft. thick, it gets bolted on during initial mining, but frequently falls as mining progresses and causes considerable support problems. When the interburden to the rider seam is greater than 6 ft. thick, the roof generally remains stable. For the stability mapping, the interburden thickness contours were used to create a grid where the roof areas with an interburden between 2 to 6 ft. were considered unstable.

Figure 5.6: Interburden thickness grid

- **Sandy mudstone unit:** Between the interburden or rider, depending on the location, and the sandstone layer there is a sandy mudstone present with an average thickness of approximately 10 ft. To create the thickness grid for the sandy mudstone, initial average thickness was decreased where the known sandstone channels eroded the mudstone using the linear feature grid module of stability mapping (See Figure 5.7).

Figure 5.7: Sandy mud stone thickness grid

- **Sandstone unit:** This unit is found above a large majority of the mine site. This unit, although present over much of the mine, only affects the mine stability when it appears as a sandstone channel that encounters the B seam or is within the immediate roof layers. The mine roof is competent in the middle of the sandstone channels where the sandstone is thick, but becomes unstable near the altered edges of the sandstone channel. A grid for the sandstone channel was subtracted from the 10-ft thick sandy mudstone grid using the grid utilities module in the stability mapping program. The sandstone unit grid was created from a grid of constant values and did not come into play with regard to the CMRR except where the combined thickness of the other units was less than the bolt length. The Sandstone grid is not illustrated in the figures since it was assigned a constant thickness of 10 ft. over the entire mine area.

All the above thickness grids were input into the CMRR module along with their individual unit rating. These unit ratings were taken from previous research done by Molinda and Mark, 1994. The damp mining conditions was considered and no surcharge adjustment was made because the uppermost unit was stronger than the lower units. The primary bolt length at the mine was 6 ft. and was used in the CMRR calculations. The final CMRR grid was calculated over the southwest mining district (see Figure 5.8).

It can be seen from the grid that the interburden to the rider seam has the most prominent effect on the roof over most the area. As the thickness of the interburden decreases towards the west, rider seam gets closer to the seam which decreases the CMRR. However, in the western part of the district, the area directly under the sandstone channels results in higher CMRR values.

Figure 5.8: Final CMRR grid

5.2.3 Pseudo-Depth Grid Generation

A topography grid was created using the provided contour data over the mine site in the StabMap gridding module (Figure 5.2). This grid was transferred into LaModel for analyzing overburden stress over the designated area. In the analyzed mine area, the longwall panels in the active district were superimposed below the previously extracted D Seam longwall panels created stress concentrations on the present workings in the B Seam (Stewart et al., 2006).

The results of the LaModel stress analysis were transferred to StabMap using the stress utility module (Figure 4.5) and the overburden and multiple seam stresses were separated and analyzed individually. The overburden stress over the B seam (see Figure 5.9) is consistent with the variation in topography as seen in the contour data (see Figure 5.2). The effect of overburden stress is expected to change the ARBS value in the final results.

Figure 5.9: Overburden stress grid

It can be seen from the multiple seam analysis, that the destressing of the gob area of the extracted longwall panels in the D seam (shown by negative stress values in Figure 5.10) over the panel in the B seam further creates higher stress concentrations over the pillars in the working district. The effect of multiple seam stress on the roof should cause the ARBS value to change in the affected area.

Figure 5.10: Multiple seam stress grid

To get an equivalent depth from the combined stresses, the pre-mining conditions needed to be assessed. This was achieved by combining both the overburden and multiple-seam stresses into an “in situ” stress grid which is the stress that the virgin coal seam would experience in the multiple-seam situation and is analogous to the overburden stress in a single seam situation. A grid for in situ stress was created (Figure 5.11). The stress grid is then converted into an effective depth, called “pseudo” depth by dividing by the stress gradient of 1.125 (Figure 5.12).

Figure 5.11: In situ stress grid

Figure 5.12: Pseudo-depth grid

5.2.4 Intersection Span Grid Generation

For this case study, most of the mining sections that were analyzed contained identical gateroad design; therefore, a constant intersection span of 25 ft. was used for the intersection span input. However, with the help of StabMap utilities different intersection spans can be used for different sections of the mine if desired.

5.2.5 Final ARBS Grid Generation

As the ARBS module is opened, a window for input appears (See Figure 5.13). The first step for was to select a location to save the output ARBS grid. Next, the mine specific intersection span and entry width were entered as 25 ft. and 12 ft. respectively and the stability factor was kept at the recommended value of 1.2. The previously created CMRR and Pseudo-Depth grids were used as input in the ARBS module. By clicking the “**Build Grid**”, the program calculates the ARBS values at every grid point and the results are dynamically stored in a file at the previously selected location. The calculations were performed according to the following equation given by Mark et al. (2001):

$$ARBS = (SF)[(0.3*(I_{SG} - I_S)) + (5.7 \log_{10} H) - (0.35*CMRR)) + 6.5] \quad (5.1)$$

Where:

ARBS = Suggested value of ARBS for given CMRR and depth of cover

SF = the Stability Factor (1.2 recommended)

I_{SG} = Suggested intersection span (ft.)

I_S = Actual intersection span (ft.)

H = Depth of cover (ft.)

CMRR = Coal Mine Roof Rating

Create Grid for ARBS [X]

Output File (.grd)

Mining Factors

Intersection Span (ft) ☐ Grid?

Entry Width (ft)

Design Factor
 Stability Factor

Geology

Coal Mine Roof Rating (CMRR) ☒ Grid?

Pseudo Depth (ft) ☒ Grid?

Unit Weight of Rock (pcf)

Figure 5.13: ARBS input form

The combined effect of roof quality and stress can clearly be seen in the ARBS intensity results (See Figure 5.14). In the areas with high CMRR (54-60) and/or low “pseudo” depth (600-800 ft.), the ARBS value goes down to 8-10 showing the impact of the stronger roof at moderate depth. In the northwest area of the mining district, where the depth is higher (1000-1600 ft.) and the CMRR is lowered (30-40) by the influence of nearby rider seams and sandstone channel margins, the required ARBS value rises to a higher value of 14-18.

Figure 5.14: Final ARBS grid

Chapter 6

Summary and Conclusions

6.1 Summary

The preceding chapters of this thesis present the development of a program that allows for the calculation of ARBS intensity values over a large area. The development of the ARBS module started with identifying the data format which is native to the mapping package SurvCADD and also compatible with some of the most widely used tools which separately analyze the effect of roof quality and stress. The next step was to develop an interface which could operate within the AutoCAD/SurvCADD environment and cooperate with the newly developed stability mapping package (Wang, 2005). To enable this application, it was decided to build the program using MS Visual C++ and the AutoCAD ObjectARX extensions. The user-friendly design of StabMap system is continued within the ARBS module which allows the advantage of using existing grids or, if absent, use a single value for calculations.

The process of calculating ARBS starts with collecting geologic and geo-mechanical data for the mine site and generating CMRR and pseudo depth grids, which serve as inputs in the ARBS module. To obtain an area wide CMRR grid, previous work done by Petrovich (2006) was extended and the areal CMRR calculation program was integrated into StabMap. For CMRR calculations, geologic data, either observational or core data, namely: strength, discontinuities, and moisture sensitivity are entered for each specific unit. The final adjustments are made based on the amount of groundwater in the mine and the strength of the rock above the uppermost unit is needed. Along with these two factors, the roof bolt length must be known to define the height of the bolting horizon. Depending on the data entered, the module generates a CMRR grid which serves as the first input for ARBS. For creating pseudo-depth grid, StabMap utilities are used to import the results from LaModel. The overburden stress and multiple seam stress are separated and combined to model the in-situ

conditions for the mine site and the result is converted into a “pseudo-depth” which is used in lieu of the depth of cover. This pseudo-depth grid is used as the second input for ARBS. The stability mapping system is also used to create intersection span grids with a constant or varied intersection span which goes in the ARBS calculations. All the input grids are then utilized inside the ARBS module and calculations are performed per equation 2.1. The final output is an ARBS grid which represents the combined effect of all the three parameters and delivers the variable required support intensity over a wide area.

Once the program was completely developed, a case study was performed to check for any errors. For the case study, a coal mine site in the state of Colorado, United States was preferred because of the availability of mine data from previous research (Stewart et al., 2006). From the available data set, four roof units were identified and thickness grids for each unit was input into the CMRR module to generate final CMRR grid. Based on the provided data, a LaModal analysis was performed for the southwestern mining district of the bottom B seam and the results were used to create a “pseudo-depth” grid. As the mine sections had same intersection span throughout, a constant intersection span grid was generated using StabMap utilities. The three input grids were used to obtain the final ARBS grid. The results correlated well to the combined effects of roof quality, stress and mine geometry. The ARBS values were found to decrease in areas with strong roof/less stress zones and increase in areas with weak roof/high stress zones.

6.2 Conclusions

The integration of ARBS into the Stability Mapping program has helped expand the utility of the ARBS required support intensity calculation to a mine wide analysis. Also, the area-based ARBS calculation can now easily incorporate more complex/accurate CMRR values taken from detailed geologic data and a more accurate stress picture by combining variable overburden stress and multiple-seam stress using LaModel. Therefore, it is anticipated that a more accurate support intensity value

will be calculated and the required bolt variables can be optimally designed on an area basis. The areal calculation provided in the paper will result in avoiding the time-consuming task of data gathering and performing similar operations over a wide area. In addition, the graphical representation of the required ARBS intensity layered over the mine maps provides an easy comprehensive illustration of the variable support density required across the mine. Ultimately, the new area-based ARBS should help the mine engineer in designing roof support systems that are more effective and thereby make the coal mine work environment safer.

Also, Implementation of the ARBS calculations in AutoCAD/SurvCADD makes StabMap a comprehensive package for performing various functions such as geologic and stress gridding inside AutoCAD/SurvCADD environment and would provide a smooth transition between different modules, likely to minimize the user's learning curve. With integration of CMRR and ARBS modules, the StabMap program can be a very useful tool to the mining engineer for better understanding of geologic and geo-mechanical characteristics of roof rock and plan roof bolt design systems accordingly to increase the safety in the working areas of the mine.

6.3 Ideas for Future Work

While going through the literature and performing the research, several areas for future research became evident. We know that, the intensity of support provided by a roof bolt depends on the density of bolt pattern which depends on number of bolts per row (N_b) and spacing between the rows (ft.), length of the bolts (L_b) and the load-bearing capacity of the bolts (C) for a given width of entry (W_e). These factors were included while developing a bolt intensity variable, ARBS given as (Mark et al., 2001):

$$ARBS = \frac{(L_b)(N_b)(C)}{(S_b)(W_e)} \quad (6.1)$$

Many of these bolt characteristics used in this equation are often kept the same, or held within tight limits at a given mine. With a grid of ARBS values at hand, the required bolt parameters can be determined to obtain the desired ARBS values at any given location. This would help the mine engineer to design the bolts of appropriate length or capacity to be used in different sections of the mines.

In addition, as roof bolts are not the only support systems used in a mine, many other types of standing supports are used in a mine. The Support Technology Optimization Program (STOP) developed by NIOSH, assists with selection and placement of various standing support systems by determining the necessary installation requirements to provide adequate support load density. The integration of STOP in stability mapping could be a next step to provide a comprehensive recommendation of the support requirements to control the convergence of the roof rock.

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