University of Nevada, Reno

A Study of Correlations between Rock Bolt Pull-Out Tests and Rock Mass Rating Scores in Underground Mining

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Mining Engineering

by

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Abstract

Rock bolt pullout testing is a common method of testing the strength of ground support in underground mining over time. Bolts that fail the pullout test fail either due to shear failure at the head of the bolt or by slipping in one piece out of structurally incompetent rock. There are many methods for quantifying rock mass strength; in this study, Bieniawski's Rock Mass Rating (RMR) system is used. This study focuses on the correlation between slipped rock bolt pullout tests with low RMR scores in underground mines. Underground mine sites participating in this study are located in Eastern Nevada, which is infamous for its low rock strength. Bolts used in this study are inflatable friction bolts, primarily Swellex bolts by Atlas Copco but with a few other manufacturers of inflatable friction bolts as well. When data was controlled for corrosive weakening of the bolt and normalized for bolt length, correlations between slipped pull-tests and low RMR scores were generally strong, positive, and statistically significant.

Dedication

I would like to dedicate this Master's Thesis to all those who helped me along the way. Dr. Kallu for all his advice and expertise, Sean Warren for all the information he was able to gather and was kind enough to share, and Chase Barnard who always came through with contacts and information when needed. I would like to thank my committee members Dr. Daemen and Dr. Motamed for taking the time to read and review my work. Finally, I would like to thank Dr. Campero for all his efforts in helping me along. And of course, all my friends and family who helped along the way. Thank you!

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1. Introduction

The Rock Mass Rating (RMR) system for rock mass strength qualification was first introduced by Bieniawski in 1973 (Bieniawski, 1973). He continued to develop and modify this system until 1989 (Bieniawski, et all. 1989). The RMR rock mass classification system's purpose is to quantify rock mass characteristics that were previously only qualitatively classified based on geologic descriptions (Bieniawski, 2011). This score is used as a preliminary assessment of ground strength and ground support design requirements (Lowson, 2013). An RMR rating is derived from a series of tables that quantify RQD, discontinuities, jointing, roughness, and ground water to obtain a score from 0 – 100 (Bieniawski, 1989).

This master's thesis will explore correlational relationships Bieniawski's RMR rating scale and failed friction rock bolt pull-out tests in underground mines in Eastern Nevada. The objective of the pull-out test is to measure the working and ultimate capacities of a rock bolt anchor (ASTM, 2014). However, upon observing pull-test in a mine, it was observed that weak rock is sometimes not able to hold on to the bolt, and the bolt started sliding out when tonnage was applied by a pull-testing machine, indicating that the bolt was not providing support to the mine wall. It is this type of failed test that this thesis attempts to correlate with low RMR scores – low scores being between 0 and 40 (Bieniawski, 1989).

2. Literature Review

Previous research on the relationship between friction bolt pull-test results has been conducted by various researchers. Brady et al. in 2005 discovered a strong correlation between bolt pullout test values measured in metric tonnes per meter and RMR. However, this research was aimed at underground design methods in weak rock, and the study focused more on bond strength than on friction bolts. Additionally, this study included different types of bolts, such as split-set and cable bolts. Finally, though the study was aimed at discovering trends in weak rock, most RMR scores fall at 60 and above, which is in the "fair" to "good" range of Bieniawski's system.

Lewis Martin et al. in 2004 also found a strong relationship between RMR and pullout values in tonnes per foot. However, this data included different types of bolts (cable, split set, and expansion bolts) compared using the same metrics without accounting for differences in properties of the bolts. Additionally, the bolt pullout data came from seven different mines, but totaled only 83 data points across all mines. Finally, it must also be noted that the RMR scores studied by Martin were all higher scores, mostly ranging between 60 and 80. Ultimately, the correlation study between RMR and pullout load was too scattered, as shown in figure 1, and so a neural network (Ward system 2003) was used to normalize to an expected curve that the data should fit. This neural net was used to find load support predictions.

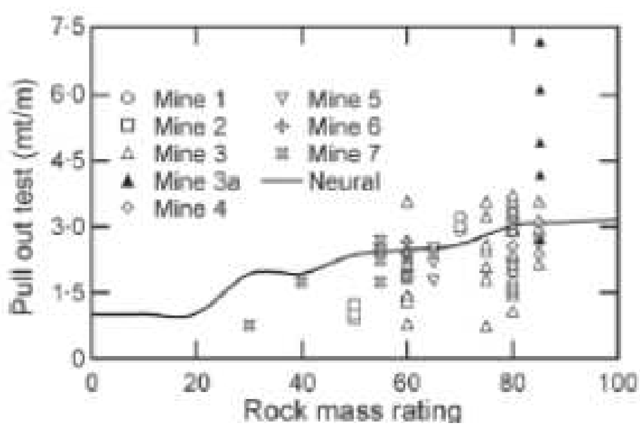


Figure 1: RMR Correlation with Neural Trendline (Martin, 2004)

Anita Soni in 2000 also explored the relationship between RMR and pullout test results. The focus of the study was on Swellex inflatable friction bolts. This study contained 37 data points total. Additionally, figures were compiled to show the correlation results for the slipped tests alone. There were 15 data points for slipped tests. Bolt pull data was collected from many different mines in Canada. A strong correlation was found, though the fact that the data is clustered around an RMR of 73 makes the statistical significance of the distributions questionable.

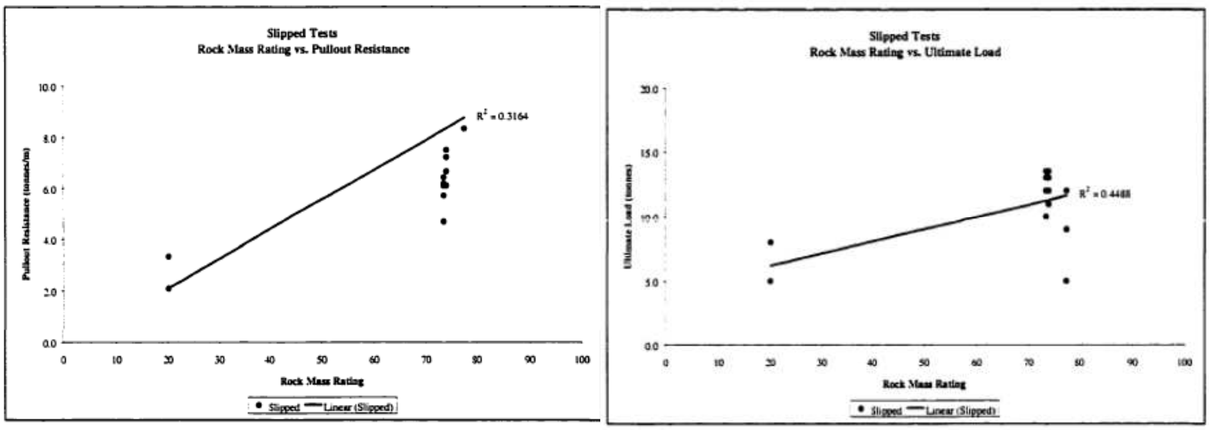


Figure 2: RMR Correlations found by Soni (Soni, 2000)

The influence of bolt length on ultimate load bearing capacity of the bolts was also explored. However, this was only explored for the standard Swellex bolt type, not the coated bolts. The correlation found in this study had an r-score of 0.21 (derived from the square root of the variance score displayed on the graph) with 275 data points.

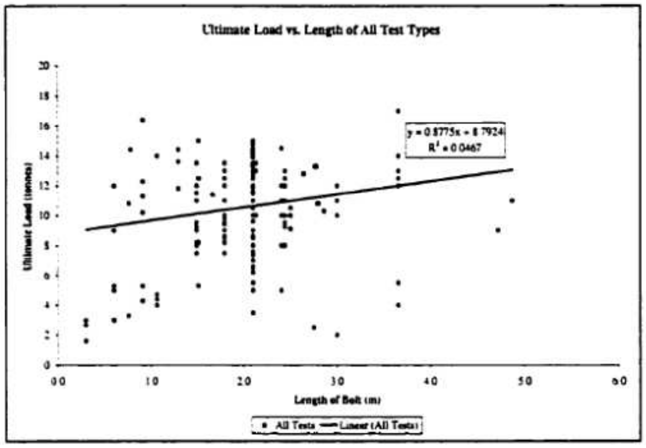


Figure 3: Bolt Length versus Pull-Test Load (Soni, 2000)

3. Geology

Three mines were used in this study, known from here on as Mine 1, Mine 2, and Mine 3. Mine 1 is located in the Getchell mining district in northern Nevada (Muntean, 2009). Mine 2 is located along the Carlin Trend (Mohling, 2002). Mine 3 is located in Lander and Eureka County in North-Eastern Nevada (McMurdo, 2009). All three mines are in Carlin-type deposits (Tosdal, 2003). Carlin-type deposits are mainly known as sedimentary rock hosted, or carbonate hosted, or disseminated gold deposits. The main ore minerals consist of disseminated sub-micron sized gold that replace mainly limestone or other carbonates (Berger, 1993).

The primary ore-controlling structure in Mine 1's district is the Getchell fault zone in Eastern Nevada. This fault strikes NNW, dips 40-55 degrees east, and has a history of normal, reverse, and strike-slip motions. Evidence suggests that gold replacement in the carbonates resulted from fluid-rock reaction and replacement (Muntean, 2009). The presence of the shallow dip faulting as well as the fluid-induced replacement actions are main causes of the weak-rock conditions observed in the Mine 1. RMR scores are generally described as very poor to poor (Sandbak, 2013).

The geology of Mine 2 is decalcified and weakly to moderately silicified rocks along the Carlin Trend. In the distant past, deep water siliceous rocks were thrust eastward over carbonate platform rocks along the Roberts Mountain thrust (Roberts, 1960). Fluid-induced replacement is again considered the most probable cause of gold deposit (Teal 2002). Most of the ore body is located in silty-sand type rock mass in the lower formations. The deposit follows the downdip extension of the carlin gold system in the footwall of the northeast-striking Hardie fault (Jackson, 2003). Rock mass rating in Mine 2 is generally rated as poor to very poor, with a highly fractured and weak rock mass (Sun, 2013).

The geology of Mine 3 is a mostly carbonate deposit, hosted by the Roberts Mountains Formation. The mine is mostly silty-limestone, similar in nature to the silty-limestone of Mine 2. Fluid-induced replacement during the Jurassic-Miocene period is the probable reason behind the emplaced gold deposits found here. Micron-sized particles of gold is found disseminated through the host rock, often found with secondary silica, iron oxides or pyrite. The location of the mine is in the Battle Mountain Eureka Trend, geographically quite close to Mines 1 and 2. The deposit is again a Carlin-type deposit (Walker, 2009).

4. Ground Support

Ground support standards in all mines include use of bolts, mesh, spiling, and shotcrete (Sun 2013, Muntean 2009, Walker 2009). Rock bolts vary in length, material, and come from different manufacturers. However, all bolts must conform to the same industry standards in order to be used (CFR, 1998), making bolts from different manufacturers comparable for engineering purposes.

Rock bolt length and type vary throughout both mines, though primarily rock bolt types are Swellex bolts manufactured by Atlas Copco. The Swellex rock bolt is made of a welded tube folded on itself and sealed at one extremity. It is expandable using a high pressure water flow provided by a pump. The bolt is expanded inside a borehole, which adds an active pressure to the interior of the rock mass. The expansion of the bolt in the borehole creates a friction and interlocking anchor, which provides full column support along the whole length of the borehole. (Minova Americas, 2009a).

Bolts are installed in a square pattern. The spacing of the bolts depends on the size of the mine opening as well as the proximity of any drift intersection within the mine. Spacing as well as bolt length also depend upon the quality of rock in the area, as well as state of water inflow (Sun, 2013).

Bolt embedment length at the three mines varies between 4.5 and 19.5 feet. Bolt coating types are uncoated, manganese, coated, and plastic coated. The yield loads vary with length, between 100 and 190 kN (Minova Americas, 2009a).

5. Core Logging

Rock Mass Rating scores are constructed using core data from drilling sites within the mine. Cores are evaluated by geologists who record the data for each intact core unit that is greater than four inches in length (Deere, 1988). Technical descriptions of rock core for engineering purposes are a recording of data related to physical discontinuities, bed thickness, joint properties, lithology, texture, rock type, weathering, void conditions, color, and hardness (Deere, 1963). Evaluating rock quality is a process that is outlined and standardized in the ASTM D6032 – 08.

6. RMR Scoring

Bieniawski's Rock Mass Rating system is laid out in the following table as created by Bieniawski in 1989 and further improved in 2011:

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125		
		(Joint water press)/(Major principal σ)	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

Discontinuity length (persistence)	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m
Rating	6	4	2	1	0
Separation (aperture)	None	< 0.1 mm	0.1 - 1.0 mm	1 - 5 mm	> 5 mm
Rating	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
Rating	6	5	3	1	0
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm
Rating	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
Ratings	6	5	3	1	0

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 - 90°	Drive with dip - Dip 20 - 45°	Dip 45 - 90°	Dip 20 - 45°
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip - Dip 45-90°	Drive against dip - Dip 20-45°	Dip 0-20 - Irrespective of strike°	
Fair	Unfavourable	Fair	

Figure 4: Bieniawski's RMR System (Bieniawski, 1973)

Values collected from the field and core samples are used as guidelines to navigate the table. Field data includes rock type information, joint properties and descriptions, and other physical properties. Values for rock strength and RQD are also factored in to the table. Scores below 40 are considered to be poor or very poor rock (Hoek, 2007).

7. RMR Block Model Construction

Block models are constructed using modeling software from Maptek Vulcan. Block models are constructed by inputting first the longitude, latitude, and elevation of the chosen geographic area of the mine, denoted as x, y, and z, respectively. Block offsets and size are decided by the user. Blocks vary in size depending on the amount and accuracy of data contained within the block (Peterson, 2012).

Databases containing relevant data can be created using Microsoft Access. This includes collar locations and elevations of bore holes, any dip or deviation of the borehole, geologic data, assay data, and geotechnical data. The databases are loaded into Vulcan after the block sizes have been decided. The databases used to construct RMR block models are drill hole databases. Both numerical and text values are used to construct the block model. Values for blocks can be interpolated across the model or limits can be set, depending on the user. For Mine 1, block values are interpolated where no empirical data was collected. For Mine 2, this is not true; the RMR values are clustered around the boreholes as shown in figure 6. RMR data from Mine 3 was delivered from the mine already tabulated in an excel table, so no correlation with block models was necessary.

8. Data Collection Methods and Procedures

Data was collected both by file sharing and field work. Mines 1 and 3 were able to transfer pullout data collected over years of testing. This data was transferred in a spreadsheet along with, in the case of Mine 1, a block model of the mine. The block model was cross referenced with the pull test locations in order to collect data.

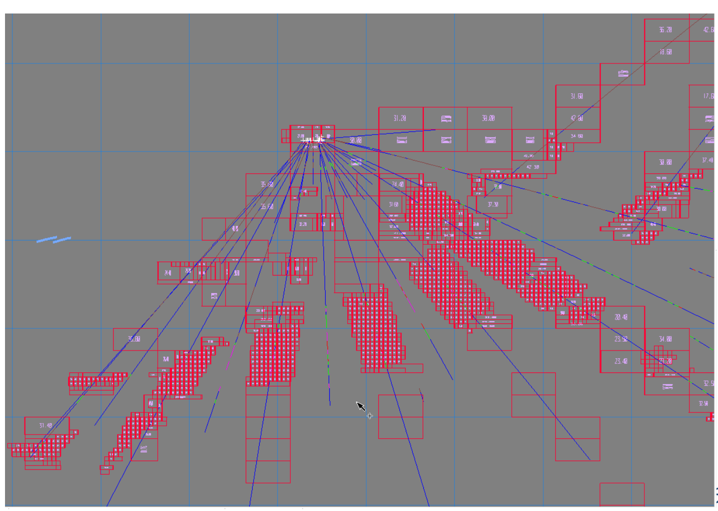
Mine 2 also provided past pull test data. However, this data was supplemented by pull tests performed and recorded in the field. Pull tests were performed in compliance with ASTM – D4435 standards on pull testing in underground mines. Pull test locations were chosen based on areas of interest in the mine as well as based on bolt age and type.

Figure 5: Pull-Testing Equipment at Mine 2

The pull-tester is designed to be accurate and portable. The adapter has a rubber sleeve that grips around the head of the bolt when the equipment is set up. The adjustable tripod insures that bolts are pulled along their main axis, to avoid shearing failure. Hydraulic pumps can pull up to 20 tonnes, though generally pull-tests range from 10 to 24 tonnes depending on bolt length and type (Minova Americas, 2009b). Pull tests were performed as part of the annual report for safety standards as well as periodically for upkeep and corrosion testing.

9. Data Analysis Procedures

After collection, data was sorted and analyzed. Pull-test information was saved in an Excel ™ spreadsheet. Pull-tests were labeled according to their location in the mine, test number, and year. It was important to note whether a bolt had slipped, broken, or passed the pull test, as well as to note what tonnage was pulled in each circumstance. RMR data had to be obtained from the block models for the mines. To correlate pull-test locations to RMR data in the block model, pull-test locations were looked at one by one. For each bolt at each location, the block model was loaded and cut so that only the data at the elevation of the pull test in question was viewed. RMR scores were shown in blocks. The blocks that fell on or near the pull test location in question were recorded as the RMR of the rock at that location, as shown in figure 6a and 6b:



(a)

(b)

Figure 6a,b: Block Model with RMR Scores Superimposed

In figure 6a, it can be seen that RMR data for both mines is based on proximity to the boreholes that had been drilled. Figure 6a is a profile view of ten boreholes drilled in Mine 2, and figure 6b is a plane view of the same area of Mine 2. The RMR scores were interpolated using Vulcan's algorithms in areas where there was no borehole. In figures 6a and 6b, the white text labels are locations of pull tests in a particular portion of the mine. RMR scores can be seen in the red blocks on the image. These scores are only the scores that correlate to the proper coordinates for the pull tests in that image, using the image slice option from Vulcan's menu. This method of correlation was used for both Mine 1 and Mine 2.

Data was further broken into categories based on bolt length, bolt type, whether or not the bolt was coated, and type of failure mode (shear or slip) present in failed tests.

10. Data

The following tables are a summary of all data collected from both mines, broken down by bolt type and embedded length:

Table 1: Bolt Descriptions at Mine 1

Failed		61
Pass		139
Total Data Points		205
Length Data	Embedded Lengths	Number of bolts
	4.5 feet	16
	5.5 feet	5
	6.5 feet	34
	7.5 feet	145
	11.5 feet	5
	Total	Fail
Coated	61	7
Uncoated	139	54

Table 2: Bolt Descriptions at Mine 2

Failed		21
Pass		89
Total Data Points		110
Length Data	Embedded Lengths	Number of bolts
	7.5 feet	109
	Total	Fail
Coated	39	8
Uncoated	70	40

Table 3: Bolt Descriptions at Mine 3

Failed	21
Pass	0
Total Data Points	21

Length Data	Embedded Lengths	Number of bolts
	1.6 feet	11
	2 feet	10
	Total	Fail
Coated	21	21

All mines used predominately Swellex bolts produced by Atlas Copco, as well as a few other inflatable bolts by Jenmar and DSI. Bolts varied between being coated with a plastic coat and being uncoated. Most bolts were made of steel; bolts made of manganese (Atlas Copco, 2014) were disregarded, as their propensity for stretching and deformation altered their behavior drastically, rendering them incomparable to steel bolts. Additionally, manganese bolts were rare, with fewer than 10 appearing in all data sets. Bolt embedment length varied in Mine 1, though the vast majority were 8-foot bolts embedded 7.5 feet. Mine 2 and Mine 3 pull tested only 8 foot bolts with a 7.5 foot embedment length.

Bolts used at Mine 2 also include some made by DSI and JSR. Additionally, Mine 2 had a larger variation in length between their bolts. However, design standards render bolts from different manufacturers comparable, and bolt length was normalized.

Mine 3 presented data from slipped tests only. Data from Mine 3 also presents a low anchorage value of 1.6 and 2 feet for all bolts. Mine 3 included inflatable bolts from DSI, JSR, and Jenmar as well as Atlas Copco.

Atlas Copco remarks that a test pulled to 8 tonnes is a non-destructive test used for maintenance and quality checking purposes. A test pulled to 12 tonnes is the destructive design load for the bolts (Minova Americas, 2009b). Tests where the bolt breaks or slides out of the rock when pulled to fewer than 8 tonnes are failed or slipped tests; similarly, if it is decided that a bolt will be pulled to failure load (12 tonnes) and it slides out or breaks before 12 tonnes, it is also called a failed or slipped test. Bolt failures occur as either a shear failure or “break”, where the bolt head is separated from bolt body entirely, or a slip, where the bolt begins to slide in one piece out of incompetent rock.

11. Data Analysis

To come to any meaningful conclusion regarding RMR scores and failed pull-out tests, the data provided and gathered at the mines had to be separated into categories. Each category was then analyzed for correlations, positive or negative, that could meaningfully describe any relationship between pull tests and rock strength. These sub categories are: bolt manufacturer, bolt type, bolt age, and bolt coating.

11.1 Bolt Manufacturer

Bolts from different manufacturers have been used over the years at each mine. Choice of manufacturer at the different mine sites depended on pricing, environmental factors, and the discretion of the ground support engineers at the time. Manufacturers used at the three different mines were:

- DYWIDAG Systems International (DSI)
- JMR Mining (JMR)
- Atlas Copco (AC)
- Jenmar

DSI produces grouted, resin, and expansion shell bolts to be used in underground mines (DSI, 2014). Though all bolts are pull-tested, there were not enough data points for specific DSI-manufactured bolts to produce a meaningful correlation. At both mines, fewer than 10 DSI bolts were included in the given and collected data. All bolts from DSI were of the uncoated variety.

JMR Mining produces rock bolts similar to DSI. However, JMR mining only appeared in one of the mine's datasets, and then had only 17 data points. As with DSI, all JMR bolts were of the uncoated variety.

Atlas Copco produces Swellex rock bolts. Swellex bolts come in coated and uncoated steel, as well as zinc-coated and manganese bolts. Atlas Copco's Swellex bolts, both coated and uncoated, were the overwhelming majority in all data sets. A table of bolt manufacturers is exhibited in Table 4.

Table 4: Bolt Manufacturers at the Three Mines

Mine 1	DSI	6
	JMR	17
	AC	183
Mine 2	AC	109
Mine 3	AC	10
	DSI	6
	Jenmar	5

11.2 Bolt Type

For Mines 1 and 2, all data points came from Swellex coated and uncoated bolts. Mine 3 was the only mine with bolts from Jenmar and DSI, all of which were coated and with an embedment length of 7.5 feet. In all cases, inflatable bolts were used in this study. Swellex steel bolts come uncoated or with bitumen or plastic coats.

Swellex steel bolts, known as “premium” or “PM”, are relatively stiff bolts used for tunneling and mining in moderate stress conditions. These bolts have a high yield load and good deformability. PM bolts can be coated or uncoated. Plastic coated bolts are coated in a plastic coating to provide corrosion protection (Atlas Copco, 2012). These bolts were most widely used at all three mine sites. Bitumen coated bolts were not used in the data collected or presented in the data received. Additionally, PM bolts can be linked together to form extra-long bolts used in hanging ground conditions, which was found to be true in fewer than 10 data points for Mine 1. However, since the linked bolts were the same make and model as the non-linked bolts, both types were comparable and were included in correlation studies.

Manganese bolts are a softer material, highly deformable and meant for compensating for ground movement. These bolts were used in an experimental capacity in Mine 2, and present in fewer than ten data points. Their different mechanical properties and behavior render them incomparable to steel inflatable bolts.

11.3 Bolt Length

Bolt length varied in Mine 1. Here, bolt length is taken to be the embedded length of a rock bolt, meaning the entire length less six inches required to remain free for pull testing and maintenance activities. Embedded lengths at Mine 2 and Mine 3 are all 7.5 feet. Embedded lengths at Mine 1 range widely, though a vast majority are also 7.5 feet. The length of the bolt greatly affects its strength properties, both in mechanical pulling capacity and skin friction values. Longer bolts are pulled to higher strengths, and have different failure loads. This means that the same tonnage applied to different bolts produces different results, regardless of rock mass strength or ground conditions.

However, it is important to note that while anchorage length is variable, materials remain the same. This indicates that if length is normalized to a value of tonnes per unit width, all bolts of the same type may be compared regardless of length. This length normalization is achieved by simply dividing the tonnes applied during testing by the embedded length of the bolt, to yield a value in tonnes/foot.

11.4 Age of Tested Bolts

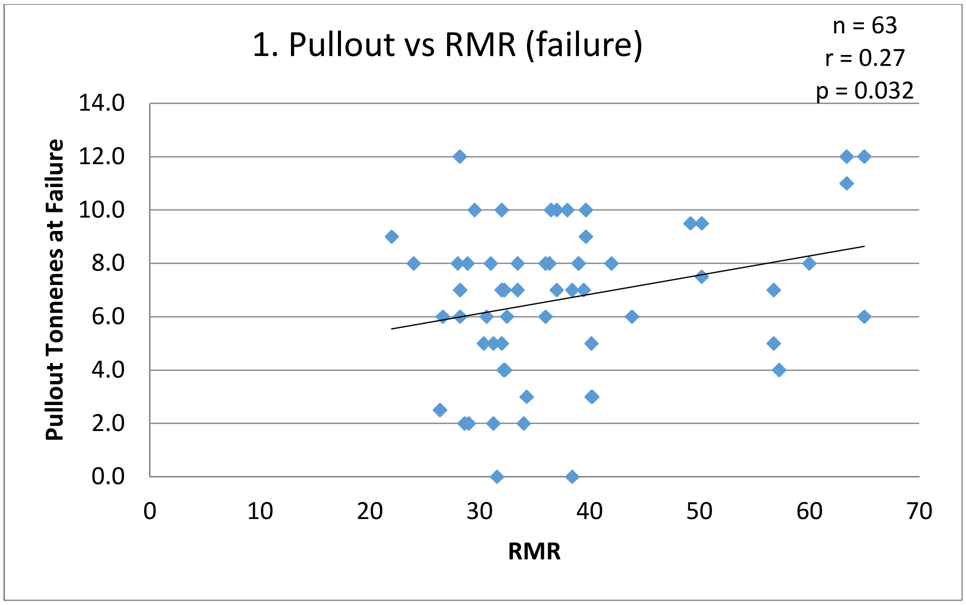
There is not much available data on correlations between bolt age and failed bolt tests. However, it is important to note that both coated and uncoated inflatable bolts can be used for up to ten years in low corrosion environments. In highly corrosive environments, the lifespan of the uncoated bolt is less than two years. Atlas Copco and other manufacturers developed its coated bolts to be used permanently (Soni, 2000). A table showing the breakdown in age of the tested bolts for Mine 2 is shown below:

Table 5: Bolt Ages at the Three Mines

Less than a year	108
Between 1 – 3 years	30
More than 3 years	5

11.5 Coating on Tested Bolts

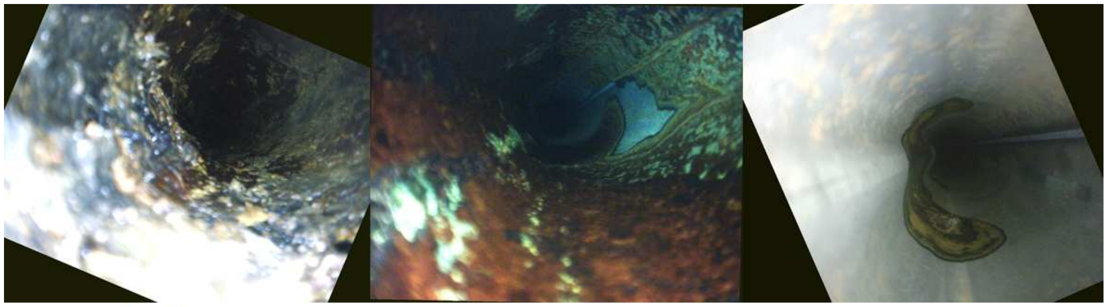
Atlas Copco produces uncoated and coated bolts in the Swellex line. The coated bolts are meant to withstand acidic and corrosive environments, much like the environments at all three mines included in this study. Without length normalized to a tonnes per foot measure, comparing rock bolt failed tests to RMR scores shows very weak correlation (graph 1):



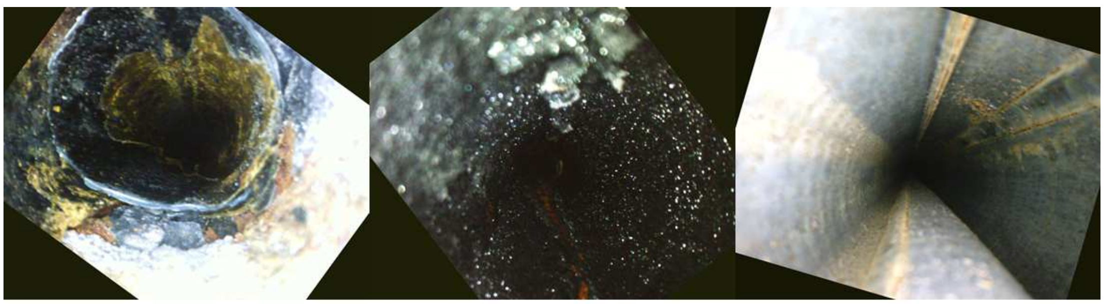
Graph 1: All Pullout Data

It is important to note that all mines exist in highly corrosive environments (Kuehn, 2008, McMurdo 2009). Often, a bolt will fail due to shear failure caused by the corrosive weakening in the first foot or two of the bolt, even though the rest of the bolt is intact and holding steady, as illustrated in the figures 7 and 8.

Figure 7: Bolts Failed due to Corrosion at Mine 2



2 inches from collar | 2-ft from collar | 4-ft from collar



8 inches from collar | 2-ft from collar | 4-ft from collar

Figure 8: Images of Installed Bolts 2 inches, 2 feet, and 4 feet from Bolt Collar

The bolts shown in figure 7 are examples of bolts that failed due to breaking. When a bolt fails due to breaking, the cause is exceedingly likely to be corrosion of the steel due to water or acidic inflow. This failure due to corrosive weakening will happen irrespective of the rock mass strength surrounding the bolt.

At this point, it becomes necessary to differentiate between the two modes of failure; when a bolt breaks near its head due to corrosive weakening, it is a “failed test”. When a bolt fails by sliding intact out of weak rock walls, it is called a “slipped test”. Since coated bolts are unlikely to fail due to corrosion, the data was further separated into coated and non-coated bolts for further study.

Though data derived from passing pullout tests is less reliable than that due to slipped or failed pullout tests, a compilation of RMR scores compared to both passed and slipped pullout scores can be evaluated for further analysis. Higher RMR scores should correlate to a passed pullout test.

Analysis of failed tests due to corrosion was conducted by assuming that all non-coated bolts that failed sheared off within the first two feet of the bolt, as demonstrated by figure 2. Since these bolts will fail at very low tonnage pulls in any type of rock mass, strong or weak, the correlation between these failed tests and their respective RMR scores is meaningless. In order to truly evaluate the correlation between low RMR scores and failed bolt tests, it was necessary to eliminate the corrosive failure aspect from the data sets.

12. Results

12.1 General Results

Analysis was done according to the parameters and decisions outlined in the analysis section. For Mines 1 and 2, only Swellex bolts produced by Atlas Copco were used in this analysis. For Mine 3, Swellex bolts were compared against other inflatable coated bolts produced by DSI and Jenmar as well as Atlas Copco. Bolt length was normalized by dividing the maximum tonnes pulled by the total embedded length of the bolt in order to compare bolts of different total lengths. Coated and uncoated bolts were then split into two groups and analyzed separately. Failed uncoated bolts are assumed to have failed due to breaking or shearing off within the first two feet of the bolt. Failed coated bolts are assumed to have slipped out of incompetent rock. The correlation between slipped tests and low RMR scores is generally positive, strong, and statistically significant (graph 3). The correlation between RMR scores and uncoated bolts is much more randomized (graph 5). The correlation between RMR scores and all pull-test results on coated bolts is positive, strong, and statistically significant (graph 4).

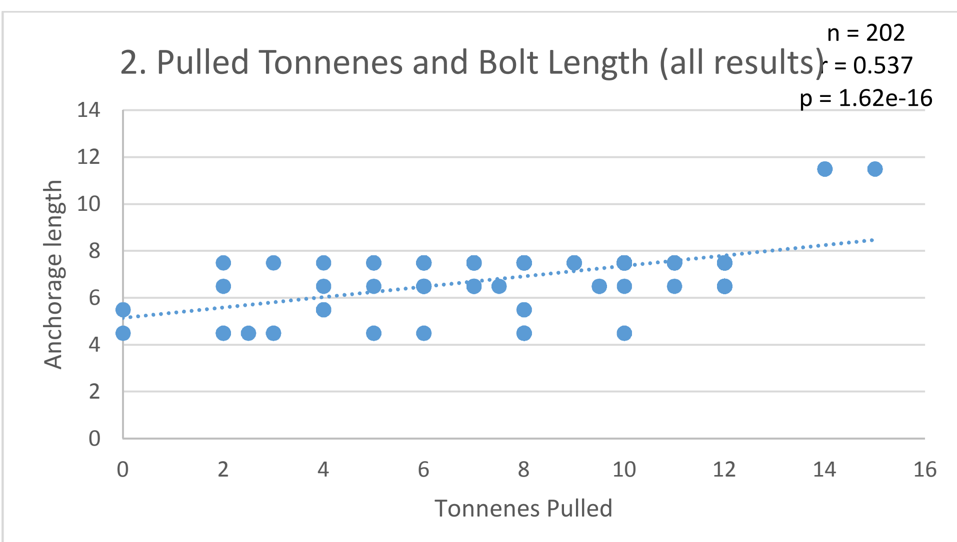
12.2 Bolt Length

When not normalized, bolt length plays a large factor in bolt strength. The increase in bolt length causes a dramatic increase in the skin friction resistance between the bolt and the rock mass, as illustrated by the equation derived by Li and Stillborg (1999):

$$P_0 = \pi d_b \int_0^L \tau_b dx$$

Equation 1: Relationship between Bolt Length and Skin Friction Resistance (Li and Stillborg, 1999)

Where L is bolt length, d_b is bolt diameter, P_0 is the applied load in tonnes, and τ_b is shear strength at the bolt interface with the rock. When bolt length is not normalized, and maximum pull is evaluated against total length, the trend becomes clear in graph 2. Longer bolts have a much higher pull capacity. Therefore, in order to compare failed pull tests, length must be normalized to a value in tonnes/foot.



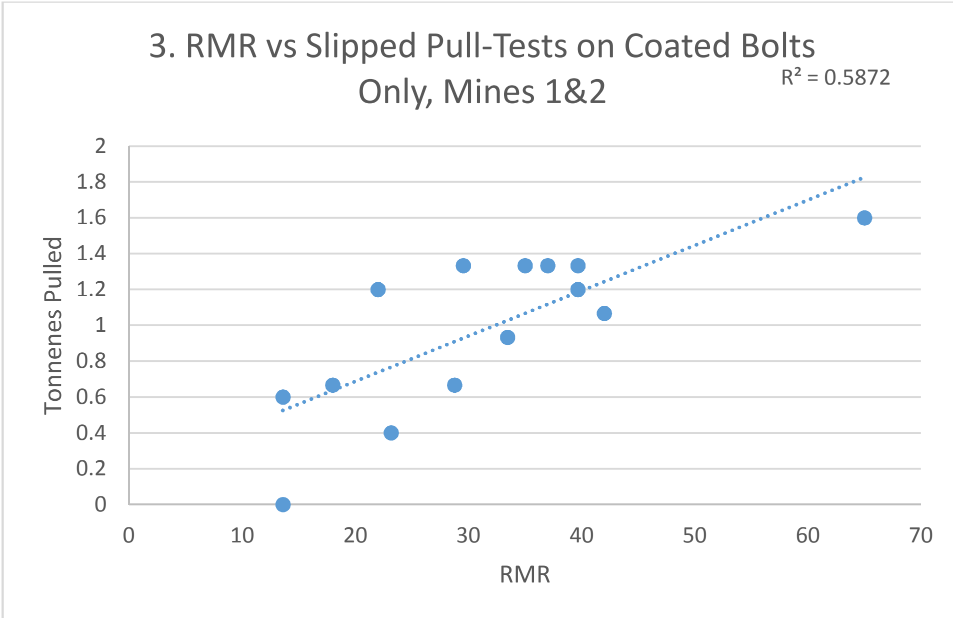
Graph 2: Relationship between Anchorage Length and Tonnage Applied during Testing; n=sample size, r = correlation strength, p = probability of statistical significance

12.3 Bolt Age

Both coated and uncoated Swellex bolts can be used for up to ten years in low corrosion environments. In highly corrosive environments, the lifespan of the uncoated bolt is less than two years. Atlas Copco developed its coated Swellex bolt to be used permanently (Soni, 2000). Since a large majority of the bolts tested are coated and are less than three years old, the age of the bolt is not considered a large factor in pull testing outcomes, though it may be if further research is conducted on older sections of mines.

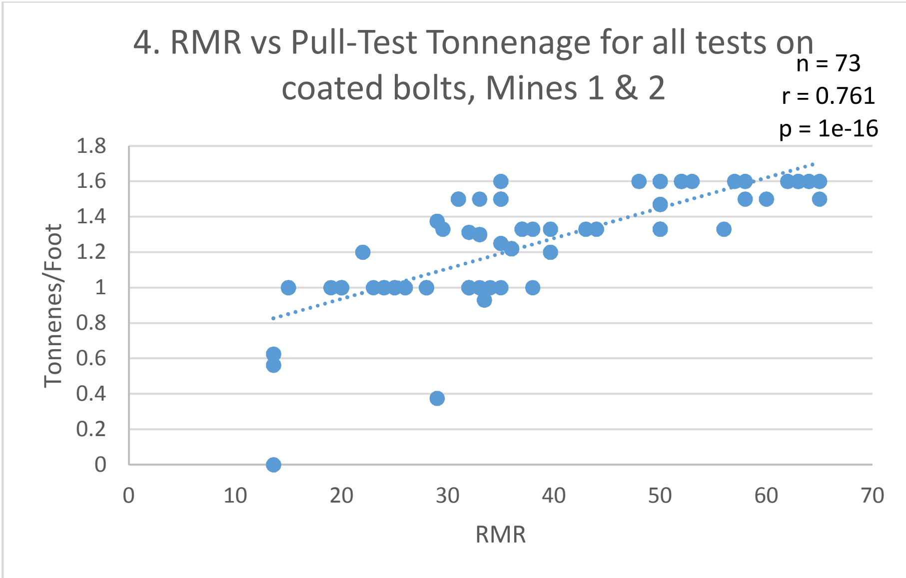
12.4 Bolt Coating

In order to evaluate slipped tests separately from failed tests due to corrosion, data was separated into "coated" and "uncoated" categories. Inflatable steel bolts are compared across all mines, and pullout test results are comparable due to similar geology in all mines. Graph number 3 illustrates the strong correlation between weak rock mass and slipped pullout test results for Mines 1 and 2. It is important to note that all but one test occurred at a low RMR score, generally accepted as a score lower than 40 on Bieniawski's scale (Bieniawski, 2011).



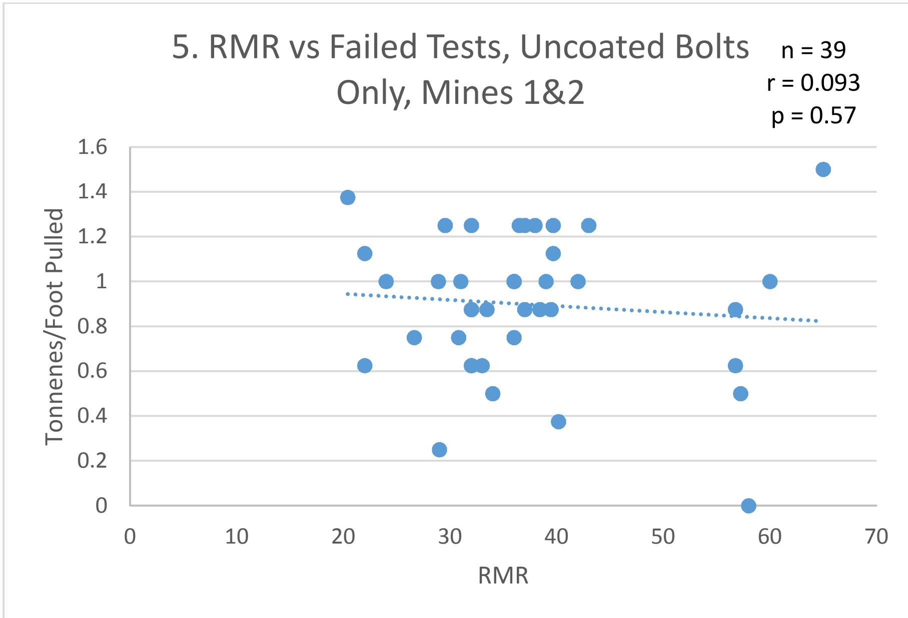
Graph 3: Relationship of RMR and Slipped Tests for Coated Bolts; n=sample size, r = correlation strength, p = probability of statistical significance

Further analysis was performed on coated bolt pullout results by combining slipped test results with passed test results. RMR strength and passed test results should still correlate at higher values of RMR. In graph 4, it is important to note that many of the scores are at RMR scores greater than 40; these are the passing pullout results. It is important to note that some rock bolts passed pullout testing even though they are hosted in weak rock. This is the expected behavior of rock bolts in underground mines.



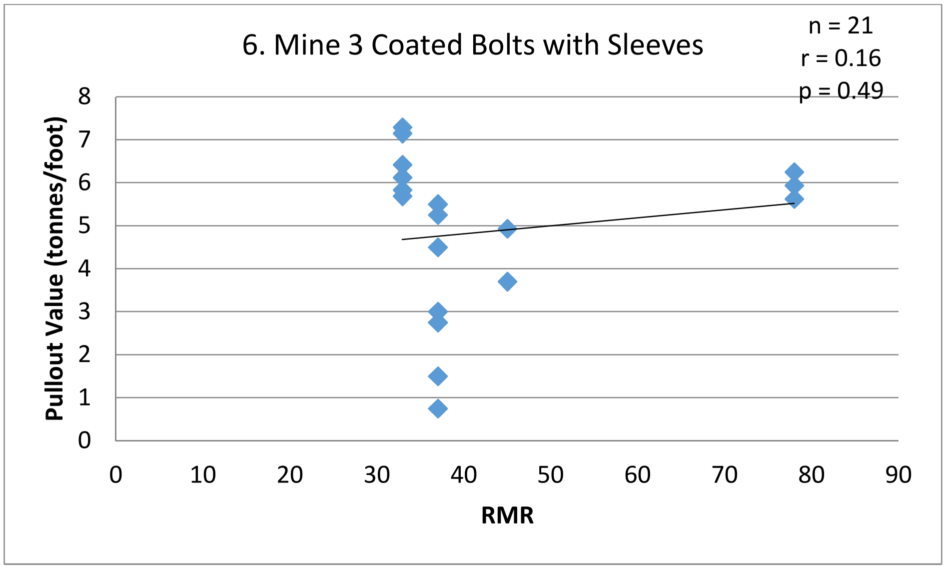
Graph 4: Relationship between RMR and Pull-Test Tonnage for All Coated Bolts: n=sample size, r = correlation strength, p = probability of statistical significance

Graph number 5 illustrates the effect of uncoated bolt failures in the data. Unlike the correlation shown for slipped tests, the distribution for failures in uncoated bolts is scattered and weak. If uncoated and coated bolts are evaluated side by side as seen in graph 1, the correlation is very weak due to the wild-card nature of uncoated bolt failures. The lack of correlation in the uncoated bolts masks the strong correlation in the coated bolts, producing the obscured correlation seen in graph 1. This indicates that uncoated bolts are likely failing due to shear failure caused by corrosive weakening of the steel bolt within the first two feet, as shown in figures 7 and 8.



Graph 5: Relationship between RMR and all Failed Tests for Uncoated Bolts n=sample size, r = correlation strength, p = probability of statistical significance

Mine 3's data was treated separately from Mine 1 and 2. Though the mine exists in similar geologic conditions and uses the same coated inflatable type bolts, this dataset included bolts that were tested with pull sleeves only. This type of test, called a two-foot anchorage test, means that a non-expansive sleeve is wrapped around the lower 6 feet of an 8 foot long uninflated bolt. When inflated, only the last two feet will inflate fully, giving the test its name (Qian and Zhou, 2012). The purpose of this is to allow the bolt to stretch and deform with the rock, making it most commonly used in highly mobile rock masses such as along a fault zone (Perry, 2014).



Graph 6: Relationship between RMR and Pull-Test Tonnes for Slipped Two-Foot Anchored Bolts at Mine 3 n=sample size, r = correlation strength, p = probability of statistical significance

The correlation in this graph is weaker than correlations in graphs 3 and 4. It is important to note the clustering of the date points. All 21 points of this pullout data for this data set included only RMR scores of 33, 37, 45, and 78. More than half the data set, 6 and 10 points respectively, had an RMR score of 33 and 37. Three points had a score of 45 and two had a score of 78.

13. Statistical analysis

To measure the correlations between each comparison, a linear regression was calculated using the Pearson method, along with a correlation coefficient (r), and a p-value. A t-test was also used to evaluate the strength of the correlation. It is important to note that a p-score with a low value shows that a correlation is statistically significant – however, in the case of graph 5, the more randomized distribution caused by the wild-card effect of uncoated bolt failures causes a higher than desirable p-score.

A p-score using the two-tailed analysis method was used due its more conservative nature. An r-score with a score closer to one indicates a strong correlation, with weaker correlations going closer to scores of zero. In the case of graph 5, this is acceptable, as a weak correlation corresponds with expected behavior of uncoated bolt failures due to corrosive weakening of the steel bolt. In the case of graph 6, a weaker correlation could be ascribed to the fact that RMR scores are clustered around 4 values, which throws the statistical significance of this dataset into question. Additionally, bolt sleeves were used in this dataset, causing a much lower anchorage length and likely affecting the data spread.

Table 6: Statistical Analysis of Pullout Data

Graph	n	r	p (2-tails)
1	63	0.27037	0.03210
2	202	0.537494	1.62e-16
3	14	0.764918	0.00232
4	73	0.760658	0.00000
5	39	0.092736	0.57445
6	21	0.15843	0.49227

14. Discussion

In this study, inflatable friction bolts were studied exclusively in order for accurate comparisons to be made of different mines' results from pull-tests. While Atlas Copco's Swellex bolt was the most common, bolts from other manufacturers were compared as well where that data was available. Since all bolts must adhere to the standards set out by the American Steel Manual (Standard D4435), for engineering purposes inflatable bolts from different manufacturers are deemed comparable in this study.

Similarly, since all three mines are located in Eastern Nevada in Carlin-type geologic deposits, data from different mines was compared and graphed on the same charts where possible. Eastern Nevada is infamous for low-strength rock mass (Mac, 2003). Faulting, jointing, mineral composition, and a host of other factors affect the RMR score of rock masses; since all three mines share similar geology, the various geologic features that affect RMR scores are similar and considered comparable.

However, the spread of the data at Mine 3 as well as the different nature of the bolt installation meant that Mine 3 data be kept separate from the data from Mines 1 and 2.

14.1 Length

Comparing pull-test results is not accurate without accounting for length. The length of the bolt has a dramatic effect on the skin-friction capacity of the bolt, which increases the pull-test capacity of the bolt. While most bolts were 8-foot bolts with a 7.5 foot anchorage length, there were some with shorter or longer embedment lengths. Consequentially, lengths were normalized for all bolts by dividing the tonnage of the pull test by the embedded length, yielding a value in tonnes per foot of bolt length anchored in the rock. This insured that all bolts were comparable regardless of length or mine location.

The effect length has on pull-test capacity is demonstrated graphically (graph 2) as well as numerically (equation 1). While Mine 2 used only 8-foot bolts with 7.5 foot embedment lengths in pull-testing, Mine 1 used bolts with embedded lengths ranging between 4.5 and 11.5 feet. Given the relative scarcity of slipped pull-test results, comparing bolts of all lengths was a necessary step in finding a meaningful correlation.

Mine 3's bolts were also normalized for different embedment length. However, Mine 3's data only included bolt pull-tests for two-foot anchorage tests, resulting in very low embedment lengths compared to the rest of the data from Mines 1 and 2. Additionally, since the majority of the length of the bolt is left uninflated during these tests, the behavior of the bolt in-hole is changed from a traditionally installed inflatable bolt (Sun, 2013). As a result, Mine 3's data was not directly compared with the data of Mine 1 and 2 (graph 6).

14.2 Coated and Uncoated Bolts

Corrosion in underground mining is in large part a result of water inflow from the formation that comprises the mine (Colin, 2008). Since the corrosion of the rock bolts generally occurred within the first two feet of the bolt, it was concluded that water flowing down the face of the rock was causing failures due to corrosive weakening of the steel (figures 1 and 2). This corrosion likely causes bolts to fail in shear. Additionally, bolts installed at an angle or pull-tested at an angle would also probably fail due to shear. Since shear failure of the bolt at or near the head of the bolt is not indicative of rock mass strength in any way, the bolt tests that failed due to shearing of the bolt were separated from the data and studied by themselves.

All bolt manufacturers produce coated and uncoated bolts. Uncoated bolts are steel bolts with no covering against corrosion. Coated bolts are coated in bitumen, rubber, plastic, etc. in order to provide protection against corrosive environments in underground environments. The effect of coating on bolts is drastic. Considerably more uncoated bolts fail than coated bolts. Since the mines exist in similarly corrosive environments, it can be concluded that uncoated bolt failure is likely due to corrosion.

Graph 5 clearly demonstrates the wild-card affect produced when uncoated bolt failures are compared with RMR scores. Bolt failures occur seemingly at random along a wide distribution of RMR scores. Given the more randomized distribution of failure, it was concluded that rock mass had little effect on uncoated bolt failures, and such failures were likely a result of shearing produced by corrosive weakening of the bolt steel where it came in contact with water inflow at the rock face. Since corrosive failures occur regardless of rock mass strength, data was separated into “coated” and “uncoated” bolt types.

Graphs 3 and 4 show results for pull-testing on coated bolts only. Here, it is much more likely that bolts failed due to “slips”, which is to say that the bolts began sliding intact out of weak rock mass as the pull-test was being performed. Coated bolt failures present a much more uniform and predictable distribution of failure, with all but one of the failures presented on graph 3 occurring below an RMR score of 40.

Graph 4 takes the correlation further by exploring pull-test results on coated bolts both in failure and passing during pull-tests. The addition of coated bolts that withstood the maximum tonnage expanded the distribution of results along a wider range of RMR scores. The r-scores in graphs 3 and 4 are similar, coming in at 0.766 and 0.761 respectively. Both p-scores are well below 0.05, indicating a strong and statistically significant correlation between low RMR scores and slipped pull-tests on coated bolts. This is similar to results obtained by Soni in 2000, though the data in this report is more plentiful and presents a more statistically significant distribution than Soni found.

While Mine 3 used coated inflatable bolts for pull-testing, the results from this mine were not as strong as results from Mines 1 and 2. While graph 6 still shows a positive correlation between low RMR scores and slipped pull-tests in uncoated bolts, the results show a much weaker correlation, with an r-score of 0.16 and a p-score well above 0.05. However, it must be noted that the data distribution of this graph casts its statistical significance into question. There are only four RMR scores presented across 21 data points. All 21 points of this pullout data included only RMR scores of 33, 37, 45, and 78. More than half the data set, 6 and 10 points respectively, had an RMR score of 33 and 37. Since the RMR score is a scale of 0 – 100, the difference between a score of 33 and 37 is minimal at best. Three points had a score of 45 and two had a score of 78.

Additionally, the nature of the bolts used in Mine 3 was altered by using six-foot long sleeves to constrict most of the length. This method, called the two-foot anchorage test, means that only the final two feet of the bolt is inflated in the hole, producing a very low anchorage length compared to data from Mines 1 and 2. This low anchorage length changes the behavior of the bolt in-hole and possibly drastically affects the results of pull-testing. There is little literature available on the subject of pull-tests with two-foot anchorage lengths. This coupled with the suspicious spread of the data presented in graph 6 renders the results from pull-testing in Mine 3 questionable. However, the graph is presented alongside more supportive graphs in the spirit of academic integrity.

15. Conclusions

Many factors present in pull-testing of bolts affect data distribution. Aside from shearing failure due to corrosion, human error such as improper bolt installation or pull-test application could result in a failed test regardless of rock mass. Additionally, human error and bias in core logging and block-model construction must also be mentioned, as a certain amount of subjectivity is present in both of those processes. However, there are many standardized rules and regulations that govern these processes.

This thesis explored data from three different mines. The datasets from these mines included many different types of bolts from different manufacturers, comprising of variable lengths and coating types on the bolts. Given the plentiful data available on inflatable bolts, these bolts were chosen as the topic for this study. The correlation between slipped pull-tests and low RMR scores in rock mass appears to be strong and statistically significant when the data is controlled for uncoated shear failures and length normalization. When controlled for these variables, correlations between slipped pull-tests and RMR scores presents at an r-score of around 0.766 and with a two-tailed p-score much less than 0.05. Though data from Mine 3 presented a much weaker correlation, the statistical significance of the distribution of the data as well as the type of pull-testing applied renders the graph questionable at best.

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