# Weak Rock Mass Span Design – Best Practices

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ABSTRACT: This paper presents ground control best practices in weak rock environments including the "Unsupported" Weak Rock Updated Span Design Curve and awareness pertaining to the potentially detrimental effects of using resin grouted rebar in weak rock masses and the false sense of security that the use of resin grouted rebar may instill. Ground support is almost always used in weak rock environments, though the type of support used can vary widely. The development of the Weak Rock Updated Span Design Curve by the addition of 463 case histories of $RMR_{76}$ values ranging from 25 to 60, has also been calibrated to four different support categories; Category A: Pattern Friction Sets, Category B: Pattern Friction Sets with Spot Bolting of Rebar, Category C: Pattern Friction Sets with Pattern Rebar Bolts and Category D: Cablebolting, Shotcrete, Spiling, Timber Sets or Underhand Cut and Fill. Design of underground man-entry type excavations in North America relies heavily upon empirical analysis. This design requires a higher Factor of Safety than other non-man entry type excavations. A comparison of the calculated ½ span failure Factor of Safety between all the categories is also presented.

## 1 INTRODUCTION

As more and more mines are being developed in weak and difficult ground conditions, this presents potentially difficult and hazardous mining conditions to workers in the industry resulting in a higher frequency of injuries and fatalities. Evidence of this can be shown by the number of fatalities and injuries resulting from uncontrolled rock falls during the time period of 1990 through 2007 (Figure 1) with a low of two (2) in 2004 and a high of 28 in 1995 and 1997 (Hoch, 2000 and Brady, 2008). In mid-1999 NIOSH started conducting visits and discussions with Nevada mines regarding weak rock and ground falls resulting in a statistical decline of ground fall related injuries over the next two years (Brady et al. 2005). An increase in ground fall related injuries occurred in 2002 and in the middle of that year, NIOSH commenced technical mine visits. There was another spike in injuries in 2005. The last two years have had relatively low numbers of ground fall related injuries. However, 2007 experienced one fatality from a fall of ground. Weak rock conditions are a concern and will continue to be in the years to come.

The relationship between span and rock quality has been studied for decades. One relationship of particular interest is that of the Critical Span Design Curve (Lang 1994) that has been widely used throughout the industry. The curve presented by Lang (1994) was later updated by Wang (2002). The Critical Span Curve is a simple and useful tool that aids in the design of underground man-entry openings. There is a need to update the Critical Span Curve for the $RMR_{76}$ range of 20-50, as there are an increasing number of mines that are operating in these weak ground conditions. The augmentation of this design to include a larger database of 463 points in the range of $RMR_{76}$ of 15-60 will increase its accuracy and reliability in such conditions.

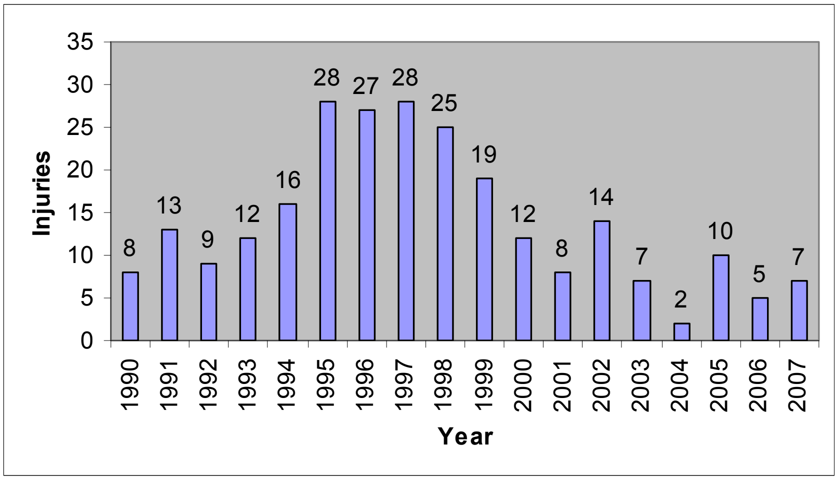


Figure 1: Ground Fall Related Injuries in Nevada, 1990-2008

Ground support is almost always used in weak rock environments. The type of support used can vary widely. The development of the weak rock augmented Span Design Curve has been divided into four (4) different support categories (with Friction Sets being Split Sets and/or Swellex type bolts); Category A: Pattern Friction Sets, Category B: Pattern Friction Sets with Spot Bolting of Rebar, Category C: Pattern Friction Sets with Pattern Rebar Bolts and Category D: Cablebolting, Shotcrete, Spiling, Timber Sets or Underhand Cut and Fill under Cemented Rock Fill. These categories have been separated in order to accurately compare similar support types with similar factors of safety. This paper presents updated span design curves for each of the support categories. The ½ span failure mechanism calculated Factor of Safety is presented for each of the above categories to show "Unsupported" conditions with a Factor of Safety less than 1.2 and "Supported" conditions with a Factor of Safety greater than 1.2. A comparison between the categories is also presented to illustrate the magnitude of an increase in support between the different categories based upon the calculated Factor of Safety.

## 2 SPAN DESIGN

Span, stability, Factor of Safety and support definitions are described in this section.

### 2.1 *Definition of Span*

The term "critical span" used by design methods/graphs refers to the largest circle that can be drawn within the boundaries of the excavation when viewed in plan (Figure 2a). This definition of span includes the overhang area that has not been supported by other means (i.e. fill from lifts below) (Figure 2b).

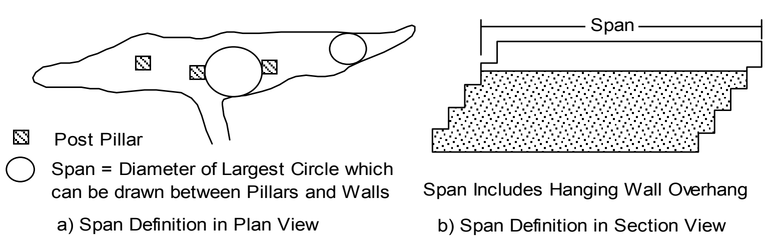


Figure 2: Span Definition (after Pakalnis and Vongpaisal 1993)

### 2.2 *Definition of Stability*

The stability of an excavation is classified into three categories, Stable, Potentially unstable and Unstable. Stable excavations have no uncontrolled falls of ground, no observed movement in the back and no extraordinary support measures have been implemented. Potentially unstable excavations have extra ground support installed to prevent potential falls of ground, movement of 1mm or more in 24 hours may have been observed (Pakalnis 2002) and an increase in the frequency of popping or cracking may indicate ground movement. Unstable excavations have collapsed where the depth of failure of the back is ½ times the span (in absence of structure related failure) and the support was not effective in maintaining stability.

When evaluating areas with shallow dipping or flat joints, a correction factor of minus 10 is applied to the final calculation of $RMR_{76}$. This correction factor is usually applied in high stress environments where these flat lying joints typically develop. In the weak rock environment, typically heavily jointed, it is expected that the addition of a flat lying joint set will play a minor role in the overall stability of the opening. Due to the amorphic nature of the already weak rock mass, the application of this correction factor for flat lying joints is questionable. Where structures of discrete wedges have been identified, these must be supported prior to employing the critical span curve.

### 2.3 *Definition of Factor of Safety*

The Factor of Safety was calculated for the ½ span failure capacity of each data point. The Factor of Safety was calculated by dividing the support capacity of the system, against the weight of a wedge that is ½ of the span. A specific gravity of 3.0 was used for each data point as it was not collected in the field. The yield and bond capacities of the system were determined from industry accepted values shown in Table 1. Both the yielding strength of the system and the bond strength (length beyond the wedge) of the system were calculated and the lesser of the two was used. A Factor of Safety above 1.0 indicates that the support system is sufficient to hold up the mass of a potential wedge failure. A Factor of Safety of 1.2 for short term development is the rule of thumb used in the mining industry. A Factor of Safety less than 1.2 is considered “Unsupported.”

Table 1: Support Properties (Brady et al. 2005 and Dehn 2007)

**ROCK BOLT PROPERTIES**

| Bolt Type | Yield Strength | Breaking Strength |
|---|---|---|
| | (tonnes) | (tonnes) |
| 5/8 inch mechanical | 6.1 | 10.2 (Grade 690MPa) |
| Split Set (SS-33) | 8.5 | 10.6 |
| Split Set (SS-39) | 12.7 | 14 |
| Standard Swellex | N/A | 11 |
| Yielding Swellex | N/A | 9.5 |
| Super Swellex | N/A | 22 |
| 20mm rebar (#6) | 12.4 | 18.5 |
| 22mm rebar (#7) | 16 | 23 |
| 25mm rebar (#8) | 20.5 | 30.8 |
| #6 Dywidag | 11.9 | 18 |
| #7 Dywidag | 16.3 | 24.5 |
| #8 Dywidag | 21.5 | 32.3 |
| #9 Dywidag | 27.2 | 40.9 |
| #10 Dywidag | 34.6 | 52 |
| 1/2 inch Cable Bolt | 15.9 | 18.8 |
| 5/8 inch Cable Bolt | 21.6 | 25.5 |
| 1/4" X 4" Strap (MS) | 25 | 39 |

#6 refers to 6/8", #7 refers to 7/8" diameter etc

**SCREEN - BAG STRENGTH 4ft X 4ft PATTERN**

| | |
|---|---|
| 4x4" Welded wire mesh (4 gauge) | Bag Strength = 3.6 tonne |
| 4x4" Welded wire mesh (6 gauge) | Bag Strength = 3.3 tonne |
| 4x4" Welded wire mesh (9 gauge) | Bag Strength = 1.9 tonne |
| 4x2" Welded wire mesh (12 gauge) | Bag Strength = 1.4 tonne |
| 2" chainlink (11 gauge bare metal) | Bag Strength = 2.9 tonne |
| 2" chainlink (11 gauge galvanized) | Bag Strength = 1.7 tonne |
| 2" chainlink (9 gauge bare metal) | Bag Strength = 3.7 tonne |
| 2" chainlink (9 gauge galvanized) | Bag Strength = 3.2 tonne |

4 gauge=.023" diam., 6gauge=0.20", 9 gauge=0.16" diam.
11 gauge=0.125", 12 gauge=0.11" diam.
shotcrete shear strength=2MPa=200tonnes/$m^2$

**BOND STRENGTH**

| Bolt Type | Bond Strength |
|---|---|
| | (tonnes/m) |
| 39mm Split Set Weak Ground | 0.75-3.6 |
| Standard Swellex Weak Ground | 8.1-13.8 |
| Cable Bolt Weak Ground | 24 |
| #6 Rebar Weak Ground | 13.6 (Dehn 2007) |
| #6 Rebar Hard Ground | 59 |

### 2.4 *Definition of Support*

#### 2.4.1 *Standard Support*

The term “design span” refers to spans that have no support and or spans that have used limited local support consisting of pattern bolting (1.8m long mechanical bolts on a 1.2m x 1.2m pattern). Local support is deemed as support that is used to confine potential blocks/loose that may open/fall due to subsequent mining activities in surrounding areas (Pakalnis and Vongpaisal 1993). Due to the dynamic nature of weak rock environments, alternate and/or increased support is typically used. Friction bolts (i.e. Split Sets and Swellex) provide yielding/passive support and shotcrete provides a rigid/active support to the opening. Spans with a Factor of Safety of less than 1.2 are deemed "Unsupported" and can be compared to the original span design database of Lang (1994). Spans with a Factor of Safety greater than 1.2 are deemed "Supported."

#### 2.4.2 *Weak Rock Support*

The database was split into four (4) support categories. These support categories were created to be able to compare similar support types with similar resultant factors of safety. These descriptions present typical bolt installation for Categories A, B, C and D respectively. Other configurations are possible and are used.

Category A is comprised of spans that were pattern bolted (typically 1.2m x 1.2m or 0.9m x 0.9m) solely with frictions sets (Split Sets and/or Swellex). The average Factor of Safety of a dead weight failure for the typical installation is 0.34. With the Factor of Safety being less than 1.0 for this category, it can be considered as "Unsupported" as was the initial graph by Lang (1994). Category B is comprised of spans that were pattern bolted (typically 1.2m x 1.2m or 0.9m x 0.9m) with frictions sets (Split Sets and/or Swellex) along with spot bolting using resin grouted rebar. The average Factor of Safety of a dead weight failure is 6.76. Category C is comprised of spans that were pattern bolted (typically 1.2m x 1.2m or 0.9m x 0.9m) with frictions sets (Split Sets and/or Swellex) and pattern bolted (typically 1.2m x 1.2m or 0.9m x 0.9m) with resin grouted rebar. The average Factor of Safety of a dead weight is 7.32. Category D is comprised of spans that were bolted with cablebolts or that were supported using another engineering designed support system such as cemented rock fill (underhand cut and fill mining), a significant application of shotcrete (typically 76mm), spiling or timber sets. The average Factor of Safety of a dead weight failure is 9.55. With the Factor of Safety of categories B, C and D being significantly greater than 1.0, these categories cannot be compared side by side with the original span graph by Lang (1994).

## 3 WEAK ROCK SPAN DESIGN

The span curve database has been augmented with a total of 463 points in the $RMR_{76}$ range of 15-60. The weak rock data has been collected from twelve (12) mines across Canada and the US. This weak rock database has been divided into four support type categories as described above.

For each category, several neural network analyses were performed. The Neuroshell Predictor program from Ward Systems was used (Ward 2003). For the span-$RMR_{76}$ relationship for each category, the networks were trained on approximately 60% of the data and verified with the remaining 40%. The categories that achieved an acceptable correlation and error, the networks were used to make stability predictions on a grid that covered an $RMR_{76}$ range from 20 to 60 and a span range from 1.5m to 13m. To determine the suitability of the calculated ½ span failure Factor of Safety in the prediction of stability, neural network analyses (genetic analysis) were performed on the entire database for each category to determine the "importance of inputs." Relationships between span, $RMR_{76}$ and FS, span and FS and $RMR_{76}$ and FS were performed. "Unsupported" refers to spans with a calculated Factor of Safety less than 1.2. The rock mass design is valid for these spans, however, care must be taken to ensure that potential structural failure planes are not present. "Supported" refers to spans with a calculated Factor of Safety that is greater than 1.2 and are supported in terms of structurally controlled failures that encompass ½ span.

### 3.1 *Category A*

The Category A database includes 47 points from seven (7) mines across North America. The neural network analysis obtained a correlation of 0.91, R-squared of 0.83 and average error of 0.14. A perfect correlation relationship is 1.0 and an acceptable correlation is above 0.80, Category A yields very good results. With the trained network, a grid of $RMR_{76}$ values of 25 to 60 and span values of 2m to 12m was trained to predict stability. Due to the factors of safety of this database being on average less than 1.0, it is fair to say that it can be compared to the original "Unsupported" database of Lang (1994). Figure 3 shows the updated weak rock curves overlaid with the 2002 updated curve.

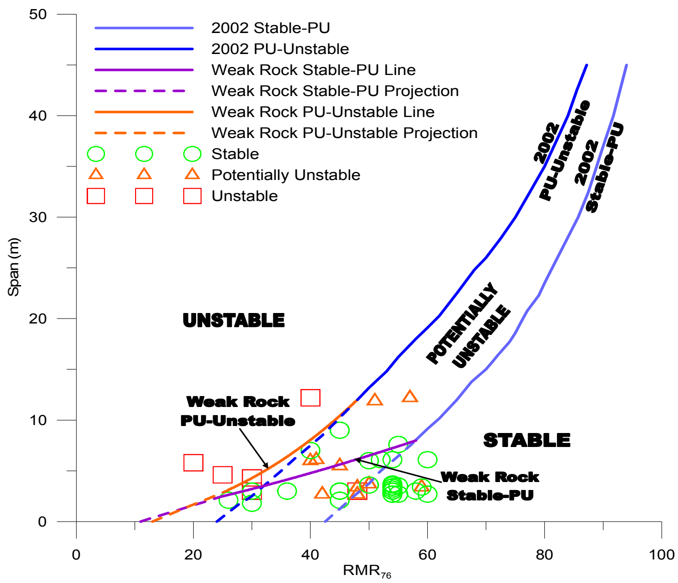

Figure 3: Category A (Pattern Friction Sets) Updated Weak Rock Curves – "Unsupported" FS<1.2

The resultant weak rock Stable/Potentially Unstable and Potentially Unstable/Unstable curves duplicate what has been seen in the field. It is known that Stable excavations are possible at lower $RMR_{76}$ values with smaller spans (Ouchi et al. 2004). However, once a certain span is exceeded, the span typically fails. This is shown with the weak rock transition curves. As the $RMR_{76}$ values decrease, the transition between Stable, Potentially Unstable and Unstable really becomes a drastic transition, at an $RMR_{76}$ of 25, between Stable and Unstable with a very small to non-existent Potentially Unstable zone where spans typically have warning signs prior to failure. On the graph, the maximum stable span at an $RMR_{76}$ of 25 is 3m. This database only has 47 cases. Typically a database this small would not be sufficient. However, these cases are well distributed over seven (7) mines and can be said to represent what is seen in weak rock environments in the North American mining industry. That being said, due to the small database, it is recommended that mines use caution around this lower end of the weak rock database and augment this database with site specific data (Ouchi et al. 2008).

#### 3.1.1 *Category A Comparison with Barton's Relationship between Q and $D_e$*

The comparison between Barton's graph and the weak rock mass curves is shown in Figure 4. The recommended ESR values for temporary openings such as those in mining applications of 3 and 5 are used. In this comparison it is shown that the weak rock mass update (Category A) of the span design curve is approaching Barton's relationship.

### 3.2 *Categories B and C*

The Category B database includes 176 points from seven (7) mines across North America and the Category C database includes 152 points from 2 mines. The Category B neural network analysis obtained a correlation of 0.90, R-squared of 0.80 and average error of 0.12 and the Category C neural network analysis obtained a correlation of 0.92, R-squared of 0.84 and average error of 0.15. Categories B and C both yield very good results. Even though these categories are significantly more supported and cannot be properly compared to the original database of Lang (1994),

Figure 5 shows the updated weak rock curves overlain with the 2002 updated curve.

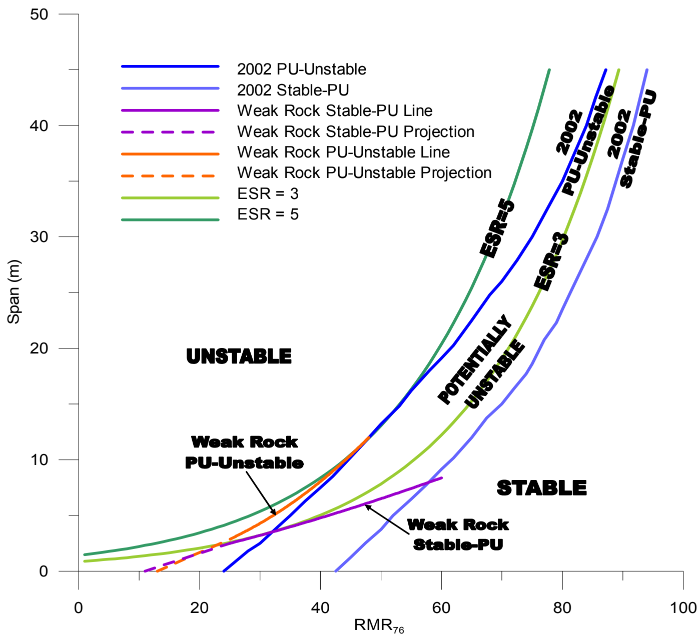


Figure 4: Category A Comparison of Span Design Curves and Barton's Relationship between Q and De

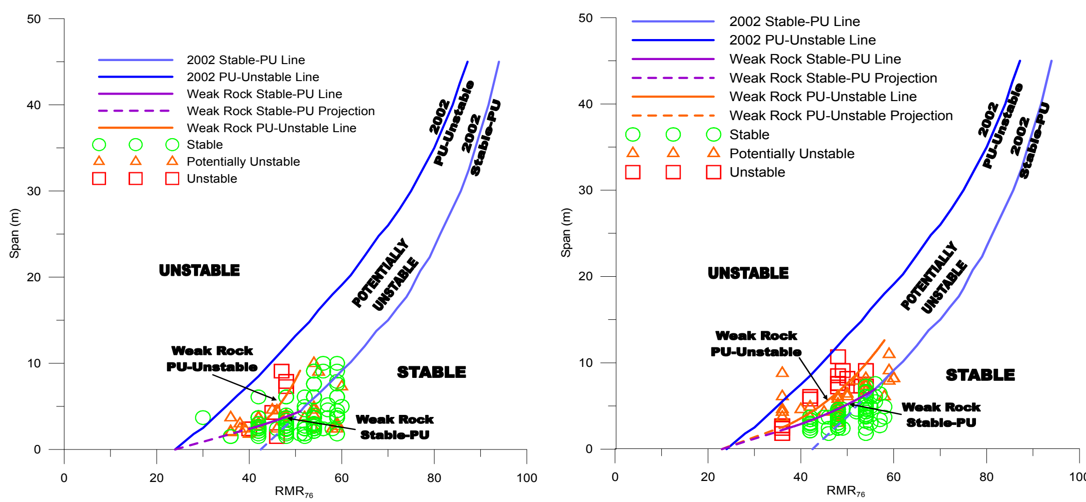


Figure 5: Categories B and C (left to right) Updated Weak Rock Curves – "Supported" FS>1.2

The resultant weak rock Stable/Potentially Unstable and Potentially Unstable/Unstable curves for Categories B and C are a little surprising Figure 6. The Stable/Potentially Unstable curve does move up indicating that stable excavations are possible down to $RMR_{76}$ values of 35. However, it has not moved up as much as the same curve for Category A (Figure 4). Also, one would suppose that the Potentially Unstable/Unstable curve would fit closer to or to the left of the existing curve due to the increased yield and bond strengths of rebar as compared to friction sets. The $RMR_{76}$ range of the databases for Categories B and C have a lower range of about 35 as compared to 20 for Category A. This could contribute to the unexpected results at the $RMR_{76}$ range less than 40. The trends exhibited in Categories B and C indicate that data in the $RMR_{76}$ 20-25 range for both graphs would be Unstable (Ouchi et al. 2008).

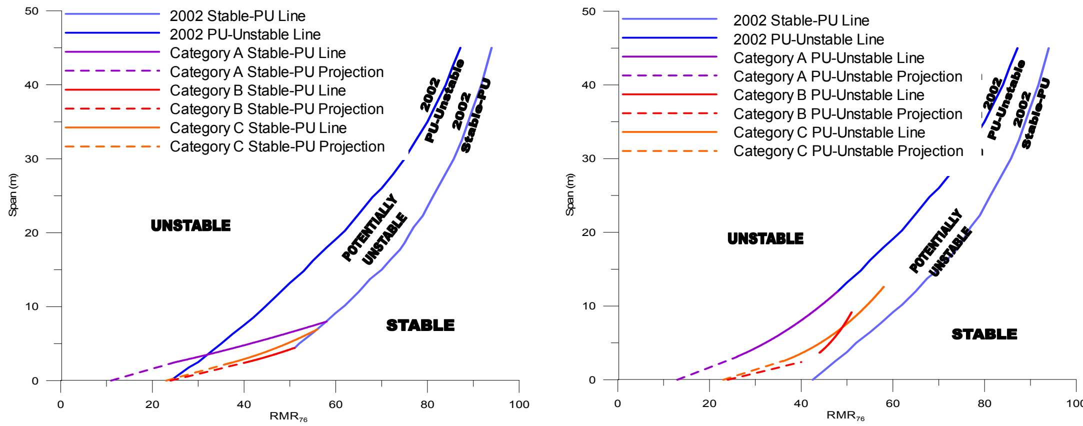

Figure 6: Comparison of Categories A, B and C Stable-PU Lines and PU-Unstable Lines (left to right)

It has been observed that resin grouted rebar is difficult to install in weak rock (Ouchi et al. 2008). Full resin coverage of the bolt is difficult to achieve due to the jointed nature of the rock mass. This incomplete coverage, leaving the toe of the bolt ungrouted, would result in a decrease in effective length of the rebar bolts. This could be a reason why there are so many spans in the previous Potentially Unstable zone that have failed. The use of resin grouted rebar in weak rock environments could give an operator a false sense of security if the bolts are not installed properly. Therefore it would be imprudent to rely on the results of Categories B and C.

### 3.3 *Category D*

The Category D database includes 88 points from 10 mines across North America. The neural network analysis obtained a correlation of 0.55, R-squared of 0.29 and average error of 0.43. This category did not achieve acceptable statistical results with the neural network analysis. This is most likely due to the varied engineered support systems which act differently on the rock mass resulting in distinct support mechanisms with different factors of safety. The data is displayed in Figure 7 to show that spans in the Unstable zone of the original "Unsupported" database of Lang (1994) may be supported with detailed engineering support design.

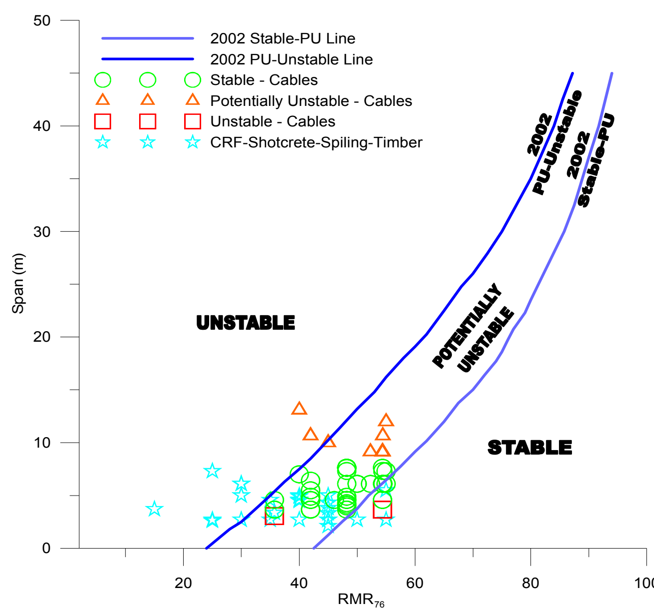


Figure 7: Category D (cablebolts, CRF, shotcrete, spiling and timber) Points on Span Design Curve (no weak rock interpretation) - "Supported" FS>1.2

### 3.4 *Factor of Safety*

A neural network analysis was performed for each category to determine the suitability of the calculated ½ span failure Factor of Safety in the prediction of stability. Each entire database was used and the "importance of inputs" outcome was chosen. The variables span, $RMR_{76}$ and FS (Factor of Safety) were compared. For all categories, no relationship was found suitablefor stability prediction. However, as seen from the best fit lines (no regression) from each category (Figure 8), the calculated FS increases as the support Categories B and C incorporate support mechanisms with greater yield and bond strengths. Category D, however, does not follow this observation. From the observations of Figure 8, Categories B and C would be approximately 20 times more supported than Category A for small spans. This increase in support decreases with span length until the span becomes greater than 10m, after which point all 4 categories support a similar amount. Category D is approximately eight times more supported than Category A for small spans. Categories A, B and C are blanket patterns of different support systems that are applied to all spans within the respective databases. Small spans within these databases would most likely not require the type of support installed, but the mine "minimum standard" would still be applied. In Category D, most all cases were carefully designed to minimize the use of costly support mechanisms while still achieving a desired Factor of Safety. This explains why Category D has a lower calculated Factor of Safety than Categories B and C for a given span.

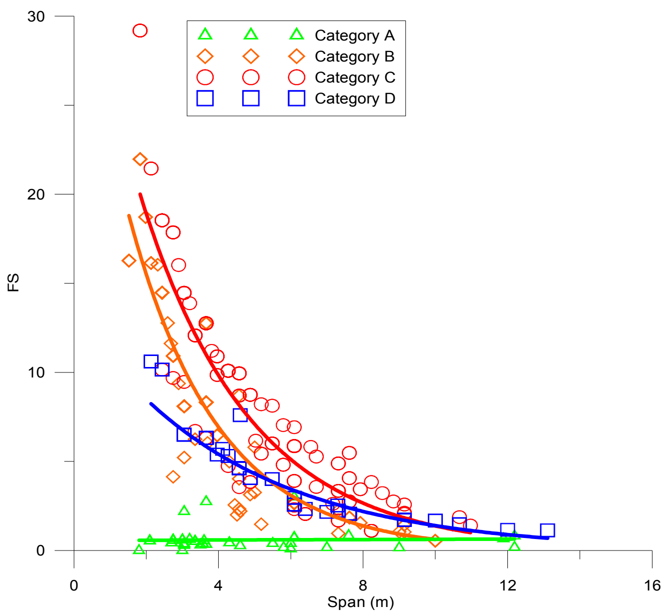


Figure 8: FS Comparison of Categories

Categories B and C have very large FS values for small spans and the FS values approach those of Category A as the span increases to over 10m. From the resin grouted installation observations noted above, it would be difficult and imprudent to rely on the results of the calculated FS for Categories B and C. The actual/in situ bond strength of resin grouted rebar may not be as assumed for the FS calculation. The FS results for these categories, as well as the results of the weak rock span design curve (

Figure 5), could give the operator a false sense of security if the bolts are not installed properly. Category A remains fairly constant at an FS of just less than 1 and reflects similar "Unsupported" conditions of the original span database (Lang, 1994). With the calculated FS being on average less than 1.0, the operator must take care in identifying potential wedge structures that will require additional support beyond what pattern friction sets provide.

From the observations above, one cannot entirely rely on the results of Categories B and C and cannot say that these categories would be approximately 20 times more supported than Category A for small spans. Categories A and D can still be compared and it is still possible to say that Category D is approximately eight times more supported than Category A for small spans. For large spans greater than 10m, all four categories support a similarly.

## 4 APPLICATION OF THE WEAK ROCK SPAN CURVE

Based upon the results of the weak rock span design and the support mechanisms available, the "Unsupported" Weak Rock Updated Span Design Curve (Category A: pattern friction sets) was employed as a design tool at one of the participating mines during 2008 (Figure 9). The "Unsupported" Weak Rock Updated Span Design Curve was used in the design of 17 headings. In addition to these spans, seven existing spans that exhibited signs of instability requiring rehabilitation were also added to the database shown in Figure 9. The calculated FS of these spans are all less than a value of 1.2 and can be considered "Unsupported". None of the spans in this test database had any identified structure that would indicate potential for a structural failure.

Of the Potentially Unstable spans, all were bolted according to the mine standards. However, the $RMR_{76}$ of these spans indicated that all but one of these spans would be Potentially Unstable or Unstable. As shown earlier these Potentially Unstable points can remain stable with additional designed support resulting in a greater Factor of Safety. The use of the "Unsupported" Weak Rock Updated Span Design Curve is an easy and useful tool for operators to use in the determination of appropriate span design and ground support application.

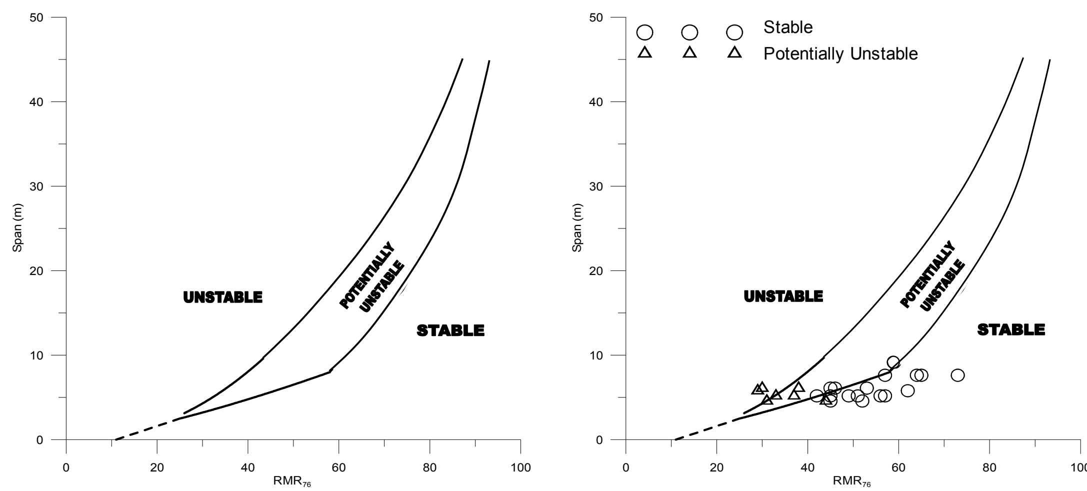


Figure 9: "Unsupported" Weak Rock Updated Span Design Curve (pattern friction sets, FS < 1.2) and 2008 use of the Weak Rock Updated Span Design Curve (left to right)

## 5 LESSONS LEARNED

It was noted that resin grouted rebar is difficult to install in weak rock. As mines are moving away from having operators work only a meter or two away from unsupported ground ("face" miners), more mechanized methods of drilling and ground support installation are being implemented. In weak rock ground support installation, it has been observed that resin grouted rebar is difficult to install. Two difficulties have been observed; the first being that the actual diameter of the hole is greater than expected, thus requiring more resin to fully encapsulate the rebar and the second being that the resin cartridges tend to either get caught in open fissures of the rock mass, breaking the tubes part way into the hole or that the resin spins out into the surrounding rock mass thus resulting in incomplete coverage of resin along the length of the bolt.

"Face" miners are able to manually insert the resin cartridges that are used. The manual insertion minimizes the risk of tearing the plastic casing of the cartridge upon insertion. The miner is also able to visually gauge the amount of resin that is required for the hole and ensure that the cartridges have reached the toe of the hole. Mechanized installation requires experienced operators who can judge the required amount of resin that is required in the hole and who have the patience to correctly install the rebar. With mechanized installation of resin grouted rebar, there is no way to ensure that the resin has reached the toe of the hole, especially if the cartridges have broken during insertion. One has to assume that if the correct number of cartridges are installed and that there is resin at the collar once the rebar is installed, that there is full encapsulation of the rebar bolt. There is no non-destructive method of testing to ensure full encapsulation of the rebar bolt. Incomplete coverage, leaving the toe of the bolt ungrouted, would result in a decrease in the effective length of the rebar bolts. Therefore, the use of resin grouted rebar in weak rock environments could give an operator a false sense of security if the bolts are not installed properly.

On the design side of support installation for weak rock masses, engineers must be aware of the significant decrease in the bond capacity of resin grouted rebar in weak rock (Table 1). It is important that weak rock mass awareness is circulated within the mining community to avoid the use of generally established hard rock values for support calculations. This is currently being undertaken by the author, Dr. Rimas Pakalnis and NIOSH in the presentation of conference papers and the initiation of short courses in areas of weak rock mass mining such as northern Nevada.

It has also been observed that the North American mining industry is moving away from the use of resin grouted rebar in weak rock masses and switching to frictions sets. Mines are also switching from Split Set type bolts to Swellex type bolts as has been observed at both of the above mentioned mines.

## 6 CONCLUSIONS

The University of British Columbia Geomechanics group and the NIOSH Spokane Research Laboratory have been conducting research in the development of safe and cost- effective underground design guidelines in weak rock environments with $RMR_{76}$ in the range of 20 to 60. An update of the Span Design Curve was conducted for this weak rock mass range. A total of 463 points were added to the database. The development of the weak rock augmented Span Design Curve has been separated into four different support categories; Pattern Friction Sets (A), Pattern Friction Sets with Spot Bolting of Rebar (B), Pattern Friction Sets with Pattern Rebar Bolts (C) and Cablebolting, Shotcrete, Spiling, Timber Sets or Underhand Cut and Fill under Cemented Rock Fill (D). Category D includes cablebolts and other engineering designed support systems such as cemented rock fill (underhand cut and fill mining), significant application of shotcrete (typically 76mm), spiling or timber sets.

Neural network analyses were conducted on the span-$RMR_{76}$ relationship for these four support categories. Categories A, B and C obtained acceptable correlation. Category D, however, did not. This is most likely due to the varied engineered support systems which act differently on the rock mass resulting in distinct support mechanisms with different factors of safety. Category A yields good results and follows what is seen in the field. These results also fit well with Barton's relationship between Q and $D_e$. At and $RMR_{76}$ value of 25, the maximum stable span is 3m. However, at an $RMR_{76}$ of 25, there is a drastic transition between the Stable/Potentially Unstable zones and the Potentially Unstable/Unstable zones. There is a very small to non-existent Potentially Unstable zone. Caution should be used when at these low $RMR_{76}$ values due to this lack of Potentially Unstable zone. Openings can very quickly go from being Stable to Unstable. Even though the database represents the North American mining industry well with 7 mines participating in the database, caution should be used as the dataset is small with 47 points. Categories B and C yielded similar results with the Stable/Potentially Unstable line moving up on the graph (increased span values). However the Potentially Unstable/Unstable line moved towards the right on the graph (increased $RMR_{76}$ values). This is unexpected, but may be explained by the difficulty experienced in the installation of resin grouted rebar. Due to this uncertainty in the accuracy of the data of Categories B and C, it would be imprudent to rely on the data interpretation in span design for these categories. Category D, the "heroic" category did not obtain positive results from the neural networks analysis, but still demonstrates that spans can be stable at lower $RMR_{76}$ values with detailed engineering support design.

The calculated ½ span failure Factor of Safety was found not to be significantly relevant in any category when applied to the prediction of stability in the relationship between the span and the $RMR_{76}$. In comparing the calculated Factor of Safety of all four categories, it was found that small spans in Category D were approximately eight times more supported (FS is eight times greater) than the corresponding small spans in Category A. As the span increased, the difference in the support capacities of the two categories diminished. At a span greater than 10m the difference in the support capacities became negligible. Due to the uncertainties identified previously, it would be imprudent to relate Categories B and C. Category A is deemed "Unsupported" with the Factor of Safety being less than 1.2. The rock mass design is valid for these spans, however, care must be taken to ensure that potential structural failure planes are not present. Category D is deemed "Supported" with the Factor of Safety being greater than 1.2 and is supported in terms of structurally controlled failures that encompass ½ span.

It has been observed that resin grouted rebar is difficult to install in weak rock. Full resin coverage of the bolt is difficult to achieve due to the jointed nature of the rock mass. This incomplete coverage, leaving the toe of the bolt ungrouted, would result in a decrease in effective length of the rebar bolts. This could be a reason why there are so many spans in the previous Potentially Unstable zone that have failed. The use of resin grouted rebar in weak rock environments could give an operator a false sense of security if the bolts are not installed properly. It has also been observed that the North American mining industry is moving away from the use of resin grouted rebar in weak rock masses and switching to frictions sets.

As with any empirical design, it is important to understand the data behind the design. These designs are for rock mass only. They do not incorporate design based upon structure and/or stress states. Small scale structure and/or changes in stress states may lead to a change in the $RMR_{76}$ of a given area. A new $RMR_{76}$ calculation may be done to reflect the change(s) and allow these empirical studies to remain valid. The empirical design graphs presented in this paper are intended to aid the experienced operator in making safe and economical design decisions.

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