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Quantifying the benefit of cable bolts as supplementary support in coal mines using the strength reduction method

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ABSTRACT: The National Institute for Occupational Safety and Health has recently implemented the strength reduction method to evaluate coal mine entry stability in FLAC3D. The method can evaluate the performance of a support system and calculate a stability factor for the entry. For this paper, two studies were analyzed to quantify the impact that cable bolts have on the stability of the entry. The first study investigated the impact of replacing fully grouted bolts with cable bolts for a variety of mining conditions. The strength reduction method was useful for quantifying the additional stability provided by the cable bolts for the mining conditions evaluated. The results were validated with case histories from the Analysis of Roof Bolt Systems (ARBS) database. The second study investigated the benefit of using an angled cable bolt with a steel strap. It was found that with a strap, the cable bolts are better utilized to provide stability. The study also found that the capacity of the cable bolt was not sufficient to provide adequate roof support when used with thicker roof straps. The strength reduction method was useful in quantifying the effectiveness of the cable bolts and determining the weakest link in the support system.

1. INTRODUCTION

The strength reduction method uses numerical models to calculate a stability factor for an excavation [1]. To determine the stability factor, the numerical models are first solved to equilibrium by using model inputs representing the expected rock strength and field stress data. If the model indicates that the design is stable, the rock strength is then reduced and the model is initialized and solved again, until collapse is indicated in the model. If the model indicates that the design is not stable, the rock strength is increased until stability is indicated in the model. The reduction factor indicates the amount that the strength has been increased or decreased. The stability factor is then calculated as the ratio of the expected rock mass strength to the rock mass strength at the onset of collapse, which is simply the inverse of the reduction factor found at the end of the model run. To demonstrate, a stability factor of 1.0 would indicate that a system is expected to be at the point of failure, less than 1.0 would indicate the potential for collapse and greater than 1.0 would indicate increasing likelihood of stability.

In coal mines, instrumented field sites are often used to determine the performance of a support system; however these sites are expensive to install and data collection is time consuming. A well-calibrated numerical model can also give indication to the effectiveness of support systems. In a calibrated numerical model it is easy to change the scenario, simply by using a different geology or stress conditions to see how the support system affects the stability of the mine roof, provided the parameters fall within the range of the calibrated models. This study uses the strength reduction method to calculate stability factors for a variety of mining conditions and the impacts of adjustments to those mining conditions. The National Institute for Occupational Safety and Health (NIOSH) has recently implemented the strength reduction method to quantify coal mine roof stability in the FLAC3D finite difference software [2]. The bisection method is used to bracket the point of collapse. The stability factor was found when the difference between the strength reduction factors of stable and failed cases was less than 0.05.

For this paper, the effectiveness of different support systems is compared and quantified using the strength reduction method. The quantification of a change to the support system is measured by the percentage difference in stability factor between two different scenarios. For example, if the method calculates a stability factor for a base case (SF_1) and then a change is made to the base case resulting in the calculation of a second stability factor (SF_2), the percentage difference between the two stability factors can be calculated as:

$$\frac{SF_2 - SF_1}{SF_1} \times 100 \quad (1)$$

By using the percentage difference between two stability factors for quantification, a positive percentage indicates that the second scenario increases stability to the entry while a negative percentage indicates that the second scenario decreases stability to the entry.

Standardized procedures have been developed at NIOSH for creating numerical model inputs from field data. The procedures have been calibrated against field monitoring results and have been shown to produce good agreement with observed excavation response and support loads [2, 3]. These cases included a variety of geological settings, depths of cover support systems and horizontal stress conditions. Although the calibration cases included cable bolt supports, the cable bolt loads were not measured. Data from an instrumented field site at a mine in Utah, where cable bolt loads were measured as the longwall approached the site [4], was selected to validate the modeling approach for cable bolts. Also measured at the field site was the stress in the core of a yield pillar. The field site was re-created in FLAC3D and the longwall pass was simulated by increasing the model boundary stress to produce matching stress values in the core of the modeled yield pillar. The modeling approach was validated by comparing the modeled bolt loads to those measured in the field.

After the approach for modeling cable bolts was validated against field measurements, the two studies analyzing the impact of cable bolts to entry stability were conducted using the strength reduction method. The first study looks into the benefit of adding cable bolts to a support system for a wide range of scenarios. The scenarios involve varying geological settings, stress conditions, and depths. The geological scenarios are representative of general coal mine roofs and are developed using the Coal Mine Roof Rating (CMRR) tool [5, 6]. Two support systems were compared against each other in each of the different scenarios. The first support system evaluated uses standard 1.8-m (6-ft) bolts, with five bolts spaced across a 6-m (20-ft) entry. The second support system increases the support in the models by replacing two of the 1.8-m (6-ft) fully grouted bolts with 4.9-m (16-ft) cable bolts. As a further validation step, the stability factors found in these models were compared against the outcomes found in the Analysis of Roof Bolt Systems (ARBS) approach, which is an empirical support design method based on observation and statistical analysis of roof bolt systems in US coal mines [7, 8].

The second study uses the strength reduction method to analyze angled cable bolts with straps, similar to the well-known roof truss support used in coal mines. In coal mines, cable bolts are often added to provide additional support for a dome of failure above the entry. A potential method of increasing the effectiveness of these cable bolts is to angle them beyond the edge of the ribline to extend over the pillars. This way, the cable bolts intersect the dome of failure at a more suitable location to provide support. However, the initial model results showed that the roof tends to fail between the angled cable bolts, negating any benefit. Further models were evaluated in which the angled cable bolts were connected by a steel strap. The strength reduction method was used to evaluate six different support configurations for a single mining condition. The support configurations include scenarios with non-angled cable bolts and angled cable bolts with different sized straps. By altering the support configuration, one change at a time, the strength reduction method can help determine the most efficient way to support the roof.

2. VALIDATION AGAINST INSTRUMENTED CABLE BOLT FIELD SITE

2.1. Background

A case history at an instrumented cable bolt site was used to validate the modeling approach and the performance of cable bolts in FLAC3D. The instrumented site was at the Crandall Canyon mine located in Utah and had a yield-abutment pillar configuration, as seen in Figure 1 [4].

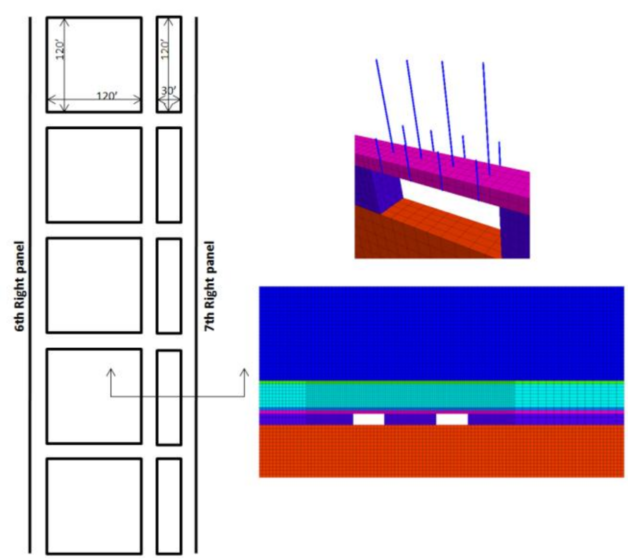


Fig. 1. The yield-abutment pillar configuration modeled to evaluate cable bolt performance. For the FLAC3D model, a partial abutment pillar, yield pillar, and partial 7th Right panel were modeled. The instruments for the test site were located in the entry between the yield pillar and 7th Right panel.

Pillar entry and cable bolt performance were monitored as the 6th Right panel and 7th Right panel were mined. The monitoring locations were in the entry between the yield pillar and 7th Right panel. A FLAC3D model was created that included a partial abutment pillar, yield pillar, and partial 7th right panel. The cable bolt loads observed in the field are used to validate the cable bolts modeled in FLAC3D.

Koehler et al. (1996) explains the roof geology as mainly of fine-grained siltstones and sandstones with occasional thin shale bands in the middle entry [4]. In the tailgate entry, the top coal thickness ranged from 0.4 to 1.2 m (1 to 4 ft) with 25 cm (10 in) of carbonaceous siltstone/claystone above. Above the carbonaceous siltstone/claystone was mostly sandstone, except for a 15-cm (6-in) coal rider that was intersected at 5.6 m (18.3 ft). A model was created from these descriptions to represent the general geology of the instrumented field site.

2.2. Numerical model development

The numerical model was developed based on best available data, following the NIOSH procedures for creating model inputs from field data [2, 3]. Rock properties from Koehler et al. (1996) and information learned from past NIOSH site visits to nearby mines helped develop the model inputs for the geological layers. Most of the roof units had strengths between 69 and 138 MPa (10,000 and 20,000 psi); however, some of the siltstone/sandstone units had strengths lower than 51.7 MPa (7500 psi). The coal had an average uniaxial compressive strength of 31 MPa (4500 psi). The carbonaceous siltstone/claystone layer directly above the top coal was modeled as shale and its strength was not clearly defined in the literature. It is assumed that at the mine, coal was left in the roof to prevent the failed carbonaceous siltstone/claystone from falling. The strength of the shale was reduced until it failed in the model, which occurred at a value of 32 MPa (4640 psi).

The supports were modeled using the structural elements available in FLAC3D. The primary support consisted of 1.5-m (5-ft) fully grouted bolts. The bolts were 22-mm (0.875-in) diameter, grade 60, with four bolts in each row. These bolts were spaced 1.5 m (5 ft) apart, placing the outside bolts approximately 0.8 m (2.5 ft) from the rib. In the model runs, the primary support was installed first and the roof was allowed to come to equilibrium after applying the initial stresses. The cable bolts used were 4.3 m (14 ft) long, 1.5 cm (0.6 in) in diameter, with a capacity of 261 kN. A resin-grout anchorage length of 1.2 m (4 ft) was used. The cables were installed between the primary support with 4 cables per row on a 1.5-m (5-ft) row spacing. The modeled primary bolt and cable bolt configuration can be seen in Figure 1.

2.3. Field results

Koehler et al. (1996) reported cable bolt loads from five locations during 6th Right panel and 7th Right panel mining. The locations included two mid-pillar sites and three crosscut sites. During 6th Right panel mining, it was reported that changes in the bolt loads were negligible. During 7th Right panel mining, changes in cable bolt loads could be observed starting approximately when the panel face was 30.5 m (100 ft) away from the instrumented test site. A summary of the reported cable bolt loads starting 30.5 m (100 ft) away from the instrumented test site is given in Figure 2.

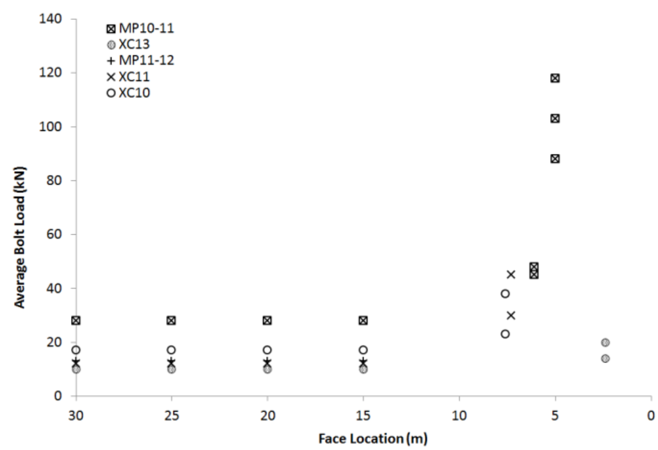


Fig. 2. Cable bolt loads reported by Koehler et al. (1996) as the face approached the instrumented test site. The loads are reported for two mid-pillar locations and three crosscut locations.

The highest cable loads were reported by the instruments located mid-pillar between crosscuts 10 and 11. The higher cable loads were stated to be caused by roof movements associated with a vertical joint structure.

Koehler et al. (1996) also measured the stress in the middle of the yield pillar as the face approached the instrumented test site. When the face was 8 m (26 ft) inby the instrument locations, the core of the yield pillar had a stress of approximately 55 MPa (8000 psi). This is the scenario that was used to validate the cable bolts in the model. For the model, the effect of the approaching face was simulated by applying a constant low velocity at the top so that the unbalanced force in the model remains very low. The effect of the constant velocity will slowly increase the vertical stress in the model. By using this approach, the stress can increase until the yield pillar ultimately fails; however the unbalanced force in the model remains very low, allowing the cable bolt loads to be accurate at specific stress levels in the yield pillar. The cable bolt loads can then be plotted when the core of the yield pillar is at a stress of 55 MPa (8000 psi).

2.4. *Model results*

The results for the FLAC3D cable bolts are shown in Figure 3. The field results are also plotted on this chart. When the face is approximately 30.5 m (100 ft) away, the cable bolt loads are roughly 12 kN, which are the pre-tension values and in the range of the field results. When the face is approximately 8 m (26 ft) away, the loads increase to 23-35 kN which are also in the range of the field results at this location. A failure plot is also included in Figure 3. The elements are colored based upon the factor of safety against failure. Elements colored red have a very low factor of safety and are very close to failure. Elements colored blue have a very high factor of safety. Elements colored light gray have already failed. The failure plot shows that the yield pillar and shale layers above the top coal are failing. The top-coal elements have a good factor of safety, illustrating that leaving coal in the roof can protect the failed shale layer from collapse. The abutment pillar in the model is also shown to be failing, agreeing with an observation made in the field by Koehler et al. (1996).

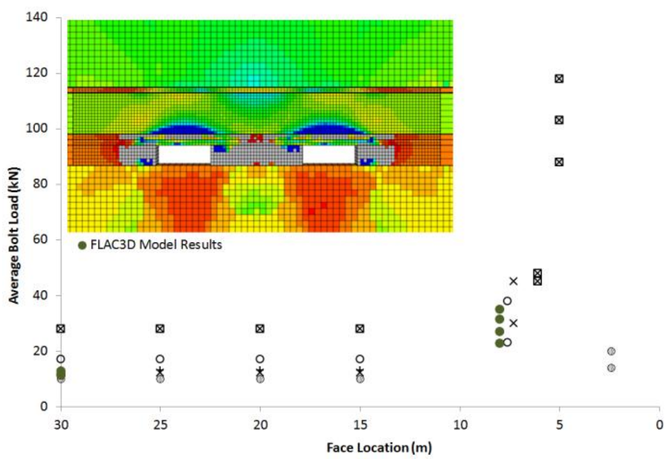


Fig. 3. The FLAC3D model results are represented by green dots and are plotted along with the field results. A failure plot is in the top left corner that shows the entire yield pillar and shale layer have started to fail when the face location is at 8.5 m (26 ft).

The results given in Figure 3 are from the best estimate of rock strengths and properties for each layer. The model was also solved with the rock strengths decreased by 15% and increased by 15% to test the sensitivity of the outcome to the estimated rock strengths. The results are shown in Figure 4. The FLAC3D results are represented by logarithmic trendlines. There are also two dashed red lines present in the figure. These red lines represent logarithmic trendlines for the highest and lowest observed field measurements. It can be seen that even if the rock strengths are underestimated or overestimated by 15%, the model results are still bounded by the highest and lowest field results. The good agreement between model results and field results validates the approach used to develop input parameters and model cable bolts in FLAC3D.

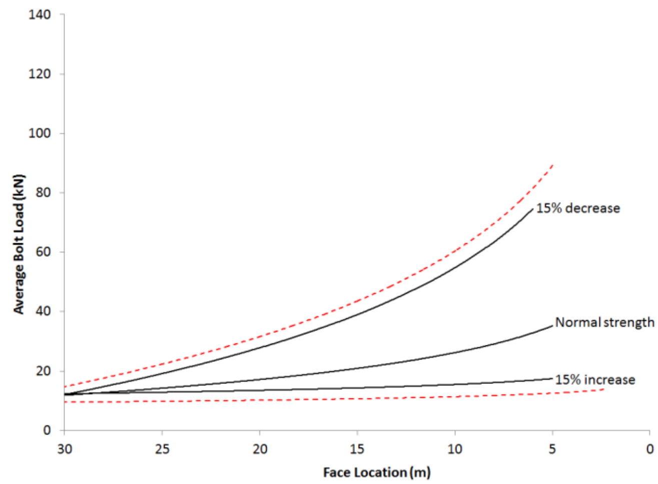


Fig. 4. Logarithmic trendlines for FLAC3D cable bolt loads from the normal strength model, 15% decreased strength model, and 15% increased strength model. The two dashed red lines represent the logarithmic trendlines from the highest and lowest field measurements. The range of cable bolt loads in the models is within the range of cable bolt loads measured in the field.

3. STUDY #1 - BENEFIT OF USING CABLES AS ADDITIONAL SUPPORT

3.1. *Model layout and support systems*

A study was completed that applied the strength reduction method to evaluate the increased stability that cable bolts provide to a coal mine entry. Two support systems were evaluated for 45 different coal mining conditions based on geology, stress, and depth, all highlighted in Table 1.

Table 1. Mining conditions simulated during study #1.

Geology	Stress	Depth
1. Uniform weak strength	1. Mining perpendicular to a high horizontal stress	100 m
2. Uniform moderate strength	2. Mining parallel to a high horizontal stress	200 m
3. Weak to strong	3. Low horizontal stress	300 m
4. Moderate strength with a weak bed		
5. Weak strength with a strong bed		

The models created in FLAC3D were representative of a standard 6-m (20-ft) wide coal mine entry. The two support systems that were evaluated during this study are shown in Figure 5. The first support system is shown on the left side of the figure and is the base case, where five 1.8-m (6-ft) fully grouted bolts are spaced equally across the entry. The second support system evaluated is on the right side of the figure, where two of the fully grouted bolts are replaced by two of the 1.8-m (6-ft) bolts with 4.9-m (16-ft) cable bolts. Replacing the grouted bolts with cable bolts is expected to improve the overall stability because of the increased length of support, but the free length of the cable bolts is likely to decrease the support system stiffness. The strength reduction method was applied to models with the two support systems for the scenarios in Table 1. For study #1, the models were run in small strain mode.

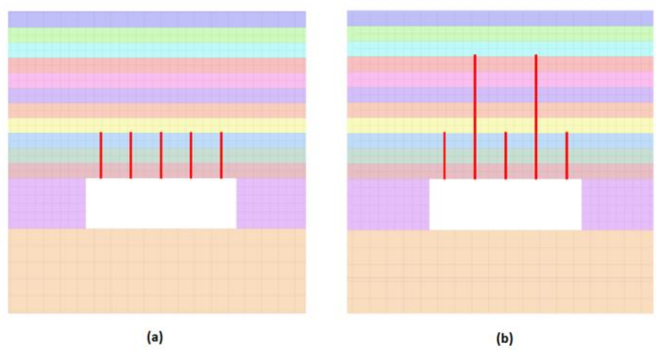


Fig. 5. The two support systems used during the study: (a) Five 6-ft fully grouted bolts equally spaced across a 20-ft entry, and (b) Three 6-ft fully grouted bolts and two 16-ft cable bolts spaced equally across a 20-ft entry.

3.2. *Geology*

Stratigraphic sequences for five geologies from Table 1 can be seen in detail in Figure 6.

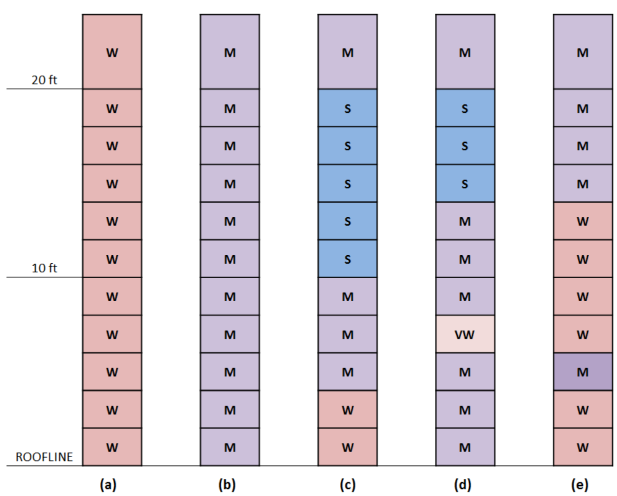


Fig. 6. The five geologies used in the study, (a) Uniform weak, (b) Uniform moderate, (c) Increasing strength, (d) Weak bed, and (e) Strong bed. Each block has a depth of 2 ft into the roof to indicate the layers that intersect the fully grouted bolts and cable bolts.

Table 2. CMRR descriptions of the four rock types used to generate the model input properties.

Description of Layer	Rock Type	Rock Strength (MPA)	Bedding Intensity Rating	Bedding Strength Rating
Very Weak	Shale	20	9	10
Weak	Shale	30	12	13
Moderate	Shale	40	15	16
Strong	Sandstone	60	18	20

The layers of each sequence are given colors and letters, which refer to the strength of the sequence. There are four colors/letters used to describe the layers: very weak (VW), weak (W), moderate (M), and strong (S). The uniaxial compressive strength and the CMRR ratings of the bedding strength and intensity are used to generate the properties for each layer, using the previously developed standardized procedures [2, 3]. The rock strength and CMRR bedding ratings used to generate the properties are given in Table 2. The coal mine roof rating is calculated using the CMRR software and inputting the sequences and values described in Figure 6 and Table 2. The CMRR values for each geology and how they can be compared to one another are as follows:

- Geology 1 - Uniform weak geology (Fig. 6a)

The uniform weak geology is a sequence of all weak strength shale layers. The coal mine roof rating along the 6-ft bolted horizon and 16-ft bolted horizon is 36.0.

- Geology 2 - Uniform moderate geology (Fig. 6b)

The uniform moderate geology is a sequence of all moderate strength shale layers. The coal mine roof rating along the 6-ft bolted horizon and 16-ft bolted horizon is 43.0.

- Geology 3 - Increasing strength geology (Fig. 6c)

The increasing strength geology contains weak strength shale for the first 4 ft (1.2 m), moderate strength shale for the next 6 ft (1.8 m), and strong sandstone high above the bolted horizon. The coal mine roof rating of the 6-ft bolted horizon is 38.3. The coal mine roof rating along the 16-ft cable bolt horizon increases to 45.1 since the 16-ft cable bolt anchors into strong sandstone. This geology can be compared to the uniform weak geology to see the effect of increasing the strengths of the rock along the bolted horizon.

- Geology 4 - Moderate geology with a very weak bed (Fig. 6d)

The moderate geology with a very weak bed contains a very weak shale bed above the 6-ft bolted horizon. The coal mine roof rating along the 6-ft bolted horizon is 40.0. A 16-ft cable bolt can be anchored into strong sandstone and the coal mine roof rating along the cable bolt increases to 42.7. This geology can be compared to the uniform moderate geology to see the effect of the weak layer above the bolted horizon.

- Geology 5 - Weak geology with a strong bed (Fig. 6e)

The weak geology with a strong bed contains a moderate strength shale bed within weak shale along the 6-ft bolted horizon. The coal mine roof rating along the 6-ft bolted horizon is 38.3. A 16-ft cable bolt can be anchored into a moderate shale layer; however, due to the presence of multiple weak beds, the coal mine roof rating along the cable bolt decreases to 37.8. Like the increasing strength geology, this geology can be compared to the uniform weak geology to see the effect of including a stronger bed along the 6-ft bolted horizon.

3.3. Field Stresses

Three stress conditions, described in Table 1, were considered that represent typical scenarios encountered during coal mining. The stress conditions are as follows:

- Stress 1 - Most unfavorable, high horizontal stress with mining in an unfavorable direction.
- Stress 2 – Unfavorable, high horizontal stress with mining in a favorable direction.
- Stress 3 – Favorable, major horizontal stress is depth dependent and equal to the vertical stress.

The high horizontal stresses for conditions 1 and 2 are dependent on the elastic moduli of the beds, using a stress calculation method developed previously [9]. The unfavorable mining direction refers to mining perpendicular to the major horizontal stress while the favorable mining direction refers to mining parallel to the major horizontal stress. For stress condition 3, the favorable stress scenario, the minor horizontal stress is approximately 60% of the vertical stress.

3.4. Implementation of the strength reduction method

A matrix of mining conditions is given in Table 1. There are 45 different scenarios that can be modeled for one support system. A stability factor is calculated for each support system in each scenario using the strength reduction method. Failure of the modeled entries was identified by monitoring a velocity point within the bolted horizon. Failure or collapse of the roof is indicated if the monitoring points are moving downwards at a constant velocity after an extended number of solution cycles.

3.5. Evaluation of strength reduction method results

The stability factors calculated from the strength reduction method in FLAC3D are shown for support system 1 in Table 3 and support system 2 in Table 4.

Table 3. Stability factors found for support system 1.

	G1	G2	G3	G4	G5
100 m					
Stress 1	1.52	2.55	1.52	1.96	*1.52*
Stress 2	1.85	3.01	2.55	2.76	*2.22*
Stress 3	2.55	5.44	4.67	5.45	*4.68*
200 m					
Stress 1	1.20	2.08	1.34	1.52	1.24
Stress 2	1.76	3.31	2.22	2.55	2.22
Stress 3	1.59	4.69	3.68	4.12	2.22
300 m					
Stress 1	1.20	1.67	1.15	1.59	1.15
Stress 2	1.39	2.08	1.85	2.38	1.67
Stress 3	1.15	3.31	1.52	2.55	1.29

Table 4. Stability factors found for support system 2.

	G1	G2	G3	G4	G5
100 m					
Stress 1	1.96	4.69	4.69	4.12	2.55
Stress 2	2.08	4.12	5.45	3.67	2.76
Stress 3	2.55	5.86	8.05	8.05	4.69
200 m					
Stress 1	1.85	3.31	2.55	2.55	2.22
Stress 2	1.76	3.67	3.01	2.76	2.37
Stress 3	2.22	5.18	4.69	4.69	2.76
300 m					
Stress 1	1.39	3.01	2.08	2.22	1.85
Stress 2	1.59	2.76	2.55	2.55	1.85
Stress 3	1.34	3.59	3.67	3.31	1.59

The impacts of depth, geology, and stress are seen in these results. In general, as the depth increases, the stability factors decrease, which is to be expected. The stability factors have good correlation with their respective coal mine roof ratings. The geology with the lowest CMRR value, Geology 1, on average has the lowest stability factors. The geology with the highest CMRR value, Geology 2, on average has the highest stability factors. Figure 7 highlights these correlations further, with a trendline given for each of the three stress conditions.

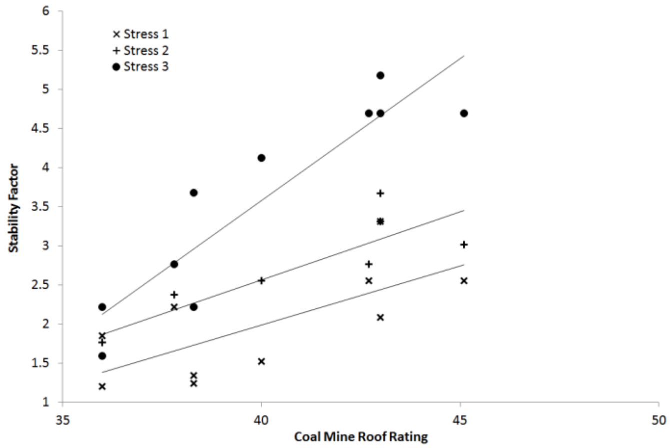


Fig. 7. The stability factors plotted against the coal mine roof rating. The plot is for the results at 200 m with the three stresses highlighted by different markers. The plot shows that for each stress, there is good a correlation with a high stability factor and high CMRR rating.

In Figure 7, the stability factors from Tables 3 and 4 for a depth of 200 m are plotted against their respective coal mine roof ratings. The data is plotted for both support system 1 and support system 2. In the chart, the three stress conditions are highlighted by different markers. For each individual stress condition, it can be seen that the stability factor increases as the coal mine roof rating increases. Stress 1, which is the most unfavorable stress condition, is observed to benefit the least from having an increase in CMRR. Stress 3, which is the favorable stress condition, is observed to benefit the most from having an increase in CMRR.

To see the effect of replacing two of the fully grouted bolts with cable bolts, the percentage difference between the stability factors from support system 1 and 2 is shown in Table 5.

Overall, the addition of cable bolts adds approximately 44% to the stability factor. Although there is benefit to adding in cable bolts for almost all geologies and depths, the most benefit is seen for Geology 3, where support system 2 increased the stability factor on average by 90%. Geology 4 sees the second-most benefit, where support system 2 increased the stability factors on average by 40%. These two geologies contain a strong sandstone unit for a 4.9-m (16-ft) cable bolt to anchor into. These trends are summarized in Table 6. The weak uniform strength geology, Geology 1, is observed in the models to have the least benefit from cable bolts. This geology does not have a strong layer for the cable bolt to anchor into.

Table 5. Percentage difference between the stability factors found for support systems 1 and 2 in FLAC3D.

	G1	G2	G3	G4	G5
100 m					
Stress 1	29.0%	83.9%	209%	110%	68.1%
Stress 2	12.5%	36.7%	114%	32.9%	24.5%
Stress 3	0.0%	7.7%	72.4%	47.7%	0.2%
200 m					
Stress 1	54.4%	59.0%	90.7%	68.1%	78.9%
Stress 2	0.0%	10.8%	35.7%	8.4%	7.0%
Stress 3	39.5%	10.6%	27.4%	13.8%	24.5%
300 m					
Stress 1	16.1%	80.3%	81.0%	39.5%	61.1%
Stress 2	14.4%	32.9%	38.1%	7.3%	10.9%
Stress 3	16.3%	8.6%	141%	29.7%	23.3%

Table 6. Percentage difference between the stability factors found for support system 1 and 2 in FLAC3D, averaged together for each geology and stress.

Geology	Percentage Difference
1	20.2%
2	36.7%
3	89.8%
4	39.7%
5	33.2%
Stress	
1	75.2%
2	25.7%
3	30.9%

A visual example of the benefit of a cable bolt can be seen in Figure 8, highlighting the difference in failure at the onset of collapse between the two support systems for Geology 3, Stress 1 and 300 m depth. The plot highlights the displacement of the roof, with the blacker shades indicating large displacements. The left side of the figure shows support system 1 and has a stability factor of 1.15. The right side of the figure shows support system 2 and has a stability factor of 2.08, an 81% increase and it can be seen that the cable bolts can control a larger dome of failure. The cable bolts are anchored into a strong strata unit, become highly loaded, and are shown to stabilize a larger area of failed roof.

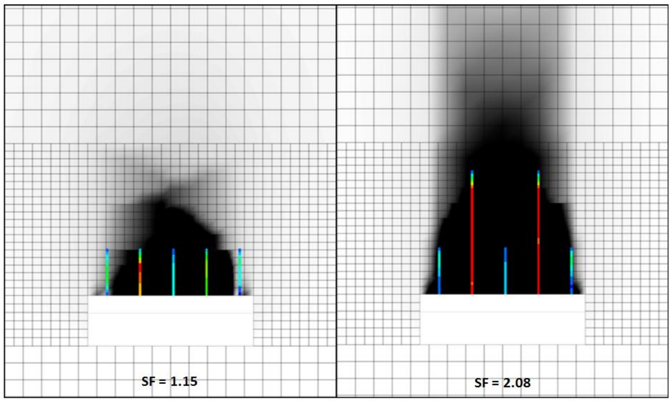


Fig. 8. Comparison of models on the onset of collapse for Geology 3, Stress 1, 300 m depth.

Trends from Table 6 relating to field stress conditions can also be observed. In the most unfavorable stress, the stability factors have an average increase of 40% after adding cable bolts for all geologies and depths. In the more favorable stress conditions, the stability factors have an average increase of 17-20% for all geologies and depths. These trends show that in high stress conditions, cable bolts are expected to have a higher benefit to coal mine entry stability.

4. VALIDATION OF STUDY #1 RESULTS AGAINST ARBS

4.1. Analysis of Roof Bolt Systems Evaluation of strength reduction method results

The Analysis of Roof Bolt Systems (ARBS) database is based on a statistical study of roof bolt performance at a number of coal mines throughout the United States [7, 8]. Case histories were collected from 37 mines with a variety of roof bolt types and patterns in a wide range of geologic environments. ARBS uses inputs that determine the performance of a roof bolt system. The inputs are the coal mine roof rating to describe the roof quality, the depth of cover, and the intersection span. ARBS suggests a design value for the intersection span, the bolt length, and the bolt capacity and pattern. The design value is supported by the extensive case history data. A stability factor can be calculated from the suggested design values. These stability factors can then be compared to the stability factors from study #1.

4.2. Calculating an ARBS stability factor

The Analysis of Roof Bolt Systems software was used to develop a stability factor for the 45 different mining conditions modeled in study #1. The ARBS stability factor was found by taking the ratio of the actual ARBS value to the ARBS value that would produce a stability factor of 1.0. ARBS stability factors were found only for support system 1, which included five 1.8-m (6-ft) fully grouted bolts. A limitation in the ARBS method exists where a stability factor cannot be calculated for a system that contains both fully grouted bolts and cable bolts. Therefore, an ARBS stability factor for support system 2, which included a combination of fully grouted bolts and cable bolts, could not be calculated for this study.

ARBS stability factors calculated for support system 1 under the five geologies and three depths from study #1 are shown in Table 7. The ARBS database inherently contains a wide range of stress conditions that cannot be separated out. Therefore an ARBS stability factor seen in Table 6 can be assumed to be an average from different stress conditions.

Table 7. ARBS stability factors calculated for entries supported by fully grouted bolts in five geologies and three depths.

Depth (m)	G1	G2	G3	G4	G5
100	1.64	2.56	1.81	2.06	1.81
200	1.36	1.92	1.48	1.64	1.48
300	1.23	1.68	1.34	1.47	1.34

4.3. Comparison to Study #1

The stability factors calculated in the numerical models (Table 3) are plotted against the stability factors determined in ARBS (Table 7) as shown in Figure 9. Since ARBS inherently contains a wide range of stress conditions, the stability factors for the numerical models had the three stresses for the geology at each depth averaged together. The stability factors calculated in the numerical models correlate strongly with the statistical results stemming from field case histories. Although there is not a 1:1 match between the model results and field results, it can be seen that the model response at varying depths and varying geology matches very well with ARBS. These matching trends are significant because they show the validity of the strength reduction method. However, a benefit of the strength reduction method is that a support system can include a combination of different bolt types. Also, the effect of the initial field stresses can be included in the evaluation of the mining scenario.

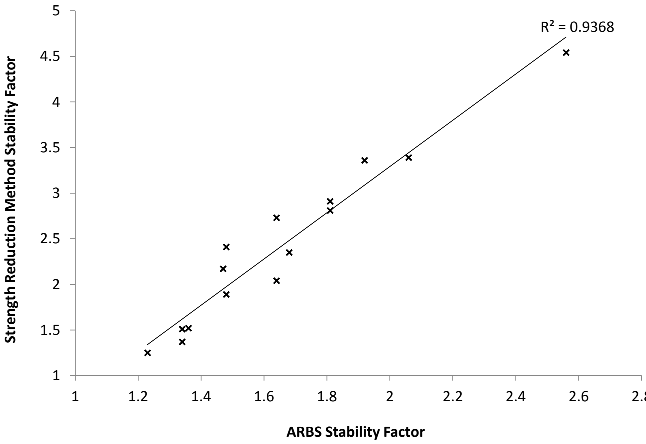


Fig. 9. Plot showing the averaged stability factors calculated in the numerical models against the stability factors calculated in ARBS for entries supported by fully grouted bolts.

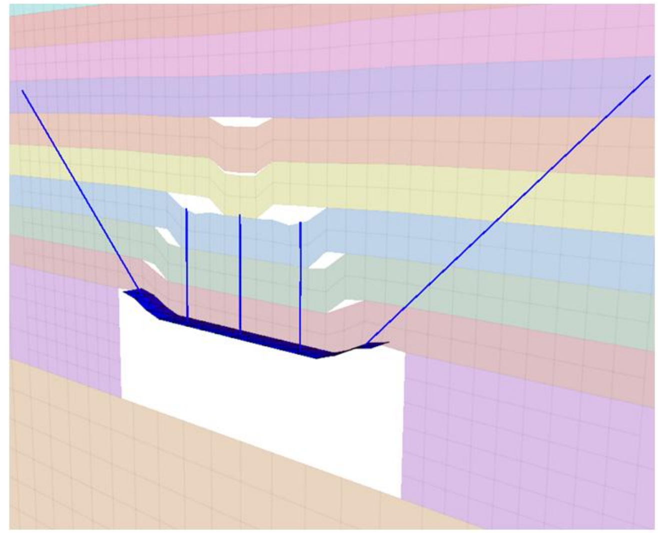


Fig. 10. Example of the entry model with angled cable bolts connected with a strap.

5. STUDY #2 - BENEFIT OF USING ANGLED CABLE BOLTS WITH STRAPS FOR SUPPORT

5.1. Model layout and support system

A study was completed using the strength reduction method to analyze the benefit of using angled cable bolts connected by a steel strap. To model the straps, the models were solved in large strain mode to account for the possible large deformation of the straps. For this reason, the stability factors in this study should not be compared to those in study #1. The straps were modeled as liners with a 3-mm (0.12-in), 6-mm (0.24-in) and 100-mm (4-in) thickness, with the first two straps being similar to the tensile strength of channels used in coal mines. The thickest strap was used to determine whether an 'extreme' strap would produce a different outcome. All the straps were 400 mm (1.3 ft) in width and 5.6 m (18 ft) long. The support used was three 1.8-m (6-ft) fully grouted bolts with two 4.9-m (16-ft) cable bolts on the edges. The cable bolts had a capacity of 400 kN and the grouted length of the cable bolts was 2.5-m (8-ft). In models that included a strap, all of the bolts were connected with the strap. An example of a strap used in conjunction with cable bolts angled at 45 degrees can be seen in Figure 10. In the figure, the strap has begun to yield as the roof displaces. The strap prevents the roof from caving and the model comes to equilibrium. The model setup in FLAC3D represents a standard 6-m (20-ft) wide coal mine entry.

5.2. Implementation of the strength reduction method

For this study Geology 3 (Figure 6c) was used again to evaluate the impact of adding a strap to models with angled cable bolts. Geology 3 contains beds with increasing strength and has coal mine roof rating of 45.1. These models were evaluated for a depth of 200 m and for a high horizontal stress with mining in an unfavorable direction. Six different support systems were evaluated using the strength reduction method and are shown in Table 8. Failure or collapse of the roof was indicated if the monitoring point in the bolted horizon had displaced downward more than 0.3 m (1 ft), which is considered to be excessive displacement.

5.3. Results and Discussion

The stability factors for the different support systems in Geology 3 are given in Table 8. The rock failure and support load at the critical strength is shown in Table 9. The critical strength is defined as the stage of the strength reduction method where the rock mass strength is reduced to the point where full collapse of the mine roof is initiated. The significance of observing the condition of the support system at this stage is the support response can be evaluated at the onset of collapse.

Table 8. Support systems evaluated for study #2. The resulting stability factor determined from the strength reduction method is also given.

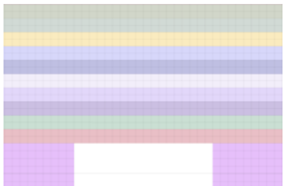
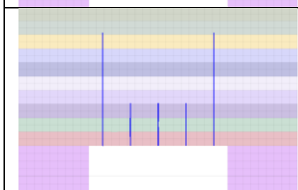
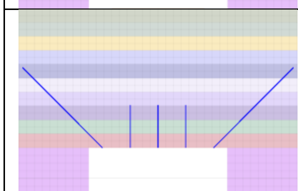
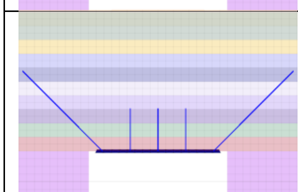
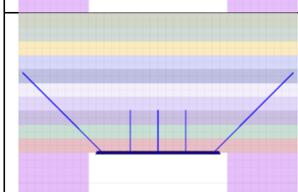
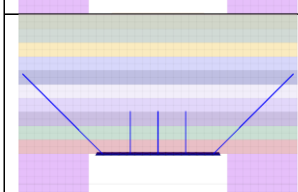
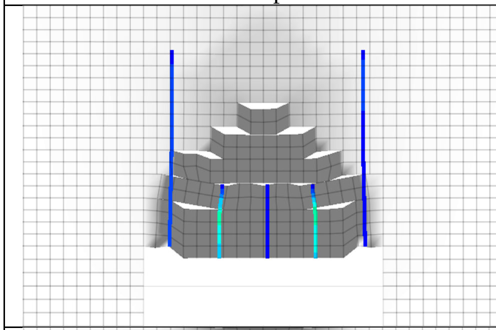
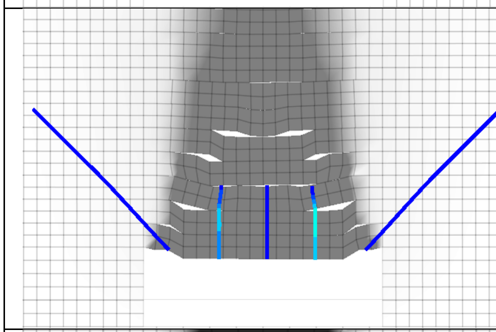
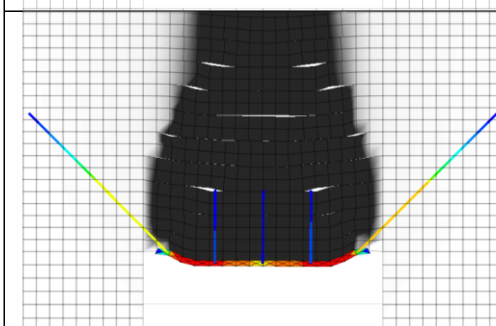
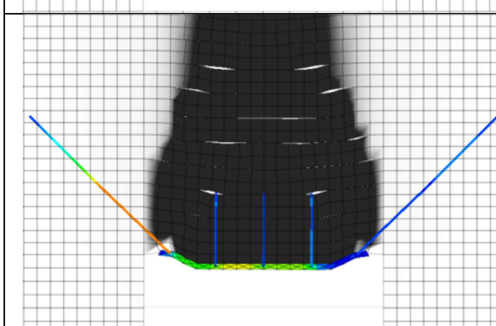
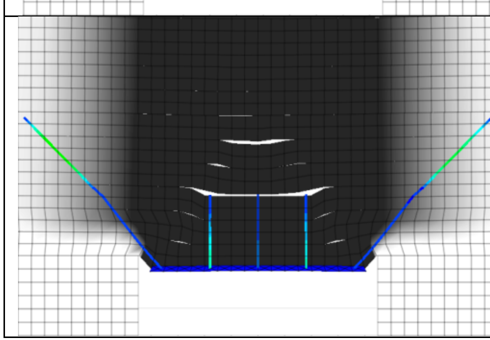
	Support Description	Stability Factor
	No support	0.92
	Non-angled cable bolts	1.59
	Angled cable bolts with no strap	1.76
	3-mm strap	2.37
	6-mm strap	2.37
	100-mm strap	3.01

Table 9. Failure plots for each support system at the critical strength.

Rock Failure and Support Load at Point of Collapse	Support Description
	Non-angled cable bolts
	Angled cable bolts with no strap
	3-mm strap
	6-mm strap
	100-mm strap

When no support is included in the entry, the expected stability factor is 0.92. This scenario is not shown in Table 9, however the collapse is initiated by the two weak shale layers detaching at the interfaces and collapsing into the entry.

When a support system is added containing non-angled cable bolts at the edge of the ribline, the stability factor of the entry is increased to 1.59. The cables are installed into the very strong sandstone and provide anchorage. However, it can be seen at the onset of collapse the cable bolts carry very little load, indicated by the blue color in Table 9. The failure of the system at the critical strength is driven by the rock collapsing between the cable bolts and the fully grouted bolts are encapsulated in the failing ground.

By angling the cable bolts by 45 degrees, the stability increases to 1.76. The angled cable bolts without a strap are shown to provide a small amount of additional stability to the entry versus installing the cable bolts straight into the roof. At the critical strength the cable bolts carry little load and the roof collapses between them.

When a 3-mm (0.12-in) strap is added to the support system, the stability factor increases to 2.37. At the onset of collapse, the strap has the ability to prevent the roof from caving by allowing the cable bolts to take a large amount of load as the strap yields. For this scenario in Table 9, the yellow colors in the cable bolt indicates the bolts are loaded to approximately half of the yield strength and the red color in the strap indicates it is yielding. The roof collapse in the model is driven by the 3-mm strap yielding until the roof displaces more than 0.3 m (1 ft) which is the threshold that the strength reduction method uses to define a collapse. Since the strap yields until the roof displaces more than 0.3 m, the strap is considered the weakest link in the system.

Next, the 3-mm (0.12-in) strap is replaced by a 6-mm (0.24-in) strap and the stability factor remains the same. The difference between the two scenarios is that the collapse is now caused by one of the cable bolts snapping which then causes the roof to cave. For this scenario in Table 9, the cable bolt on the right side of the entry shows no load because it has snapped at the onset of collapse. The roof collapse in the model is driven by the cable bolt yield strength not being matched adequately for the thickness of the strap. The yield in the 6-mm strap is much less when compared to the 3-mm strap; however the roof only collapses into the entry when one of the cable bolts snaps. Since the cable bolt is not strong enough to carry the load transferred by the strap, the cable bolt is considered to be the weakest link.

Lastly, a very thick 100-mm (4-in) strap was added to determine the performance of the system using an extreme strap strength that will not yield. For the very thick strap, the stability factor was found to be 3.01. The very thick strap does not yield and the cables take an extremely high load until both of them snap. The collapse in this case is driven by the bolts snapping and the roof caving in. The cable bolt is the still the weakest link the in the system, but the stability factor is much higher because the very thick strap delays the roof sag when compared to the 6-mm strap.

For this geologic scenario, adding a strap to an angled cable bolt increases the stability factor significantly. However, to gain the benefits of a thicker strap, the capacity of the cable bolt needs to increase.

6. CONCLUSIONS

For this paper, the strength reduction method was used to quantify the impact of cable bolts to support systems installed in coal mine entries. The quantification of the impact is measured by the difference in stability factor between two scenarios. First, a study was completed that analyzed two support systems for a wide variety of geologic, stress, and depth scenarios. The difference in the two systems is that one system replaced two fully grouted bolts with cable bolts. It was found that cable bolts have a strong impact when they can be installed in a strong layer to provide anchorage. Also, it was found that cable bolts have a strong impact in improving stability for any geologic scenario when mining in a very unfavorable stress condition. These types of outcomes were expected, but by showing strong correlation with comparable trends found in well-documented empirical studies such as the Coal Mine Roof Rating (CMRR) and Analysis of Roof Bolt Systems (ARBS), the strength reduction method can be validated as a useful tool. For this type of analysis with changing mine conditions, the strength reduction method was found to be beneficial because it quantified how entry stability is affected by circumstances such as an increase in depth or the introduction of a weak bed above the bolted horizon.

The second study measured the impact of a variety of support systems for a single mining condition. The study was able to illustrate that angled cable bolts held together with a strap can provide additional stability to a coal mine entry. More importantly, the strength reduction method was beneficial because it can be used to quantify the impact of slight changes to a support system and find the weakest link. For example, it was found that for a very strong roof, there was no difference in stability when using an angled cable bolt with a 3-mm or 6-mm strap. However, the collapse in the mine roof was driven by different factors, giving a mine engineer an indication of how the support system is performing and how it can be improved.

The cable bolts modeled during the study were initially calibrated using field site data to develop a reasonable model. The two studies that investigated the impact of these cable bolts found results that should be expected, such as the replacement of a fully grouted bolt with a longer cable bolt typically provides more stability. However, the use of the strength reduction method is significant because these expected findings can now be quantified by comparing the stability factors. The strength reduction method can be viewed as an additional tool for mine engineers provided it is used within the range of parameters used for calibration. These models can help the mine engineer quickly assess advantages and disadvantages of varying support systems and mining conditions without developing an instrumented field site.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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