

Application of the strength reduction method in coal mine roof support design

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ABSTRACT

Ground falls represent a significant proportion of injuries and fatalities in underground coal mines in the US. During 2013, ground falls were responsible for 4 of the 14 fatalities and 16.6% of the 1,577 reportable lost-time injuries. In addition, each year about 400 to 500 large roof falls are reported that can extend up to or above the bolted horizon. Support design for coal mine entries is largely based on past experience and a trial-and-error approach. A numerical model-based approach for support design is presented in which calibrated models are used to determine a stability factor for a supported entry. The stability factor is determined using the strength reduction method (SRM). Applying this technique, the relative merits of various support systems can be evaluated. The numerical models allow the contribution of individual support units to overall stability to be assessed. Two case histories are presented. In the first case the SRM approach is applied to assess the use of passive cable anchors as primary support in a room-and-pillar coal mine. The second demonstrates how the SRM approach was used to evaluate the impact of angled bolts at the rib-roof corner on roof stability. It is concluded that the SRM approach provides useful information to assess the overall degree of stability achieved by a support system, and allows support elements to be optimized for particular geological and stress conditions.

KEYWORDS: FLAC3D; coal mine roof support; strength reduction method; cable bolts

1. INTRODUCTION

Ground falls remain a significant cause of fatalities and injuries in underground coal mines. Over the ten-year period of 2005 through 2014, falls of ground were responsible for 32% of all fatalities in underground coal mines (Mine Safety and Health Administration (MSHA), 2015). While improvements are continuously being made in support technology, design, and application, underground mine workers remain exposed to the hazard of ground falls on a daily basis. Factors contributing to ground falls may include natural planes of weakness within the rock mass, unfavorable loading conditions, low rock strength, unusual depositional features, and dynamic loading events. Furthermore, a specific roof fall may be related to more than one contributing factor. Ground falls can be reduced by supporting the excavation walls and by modifying the excavation layout to improve ground stability.

2. SUPPORT DESIGN APPROACHES

Mine operators in the United States are expected to develop and follow a roof control plan, approved by the MSHA district manager, which is suitable to the prevailing ground conditions and mining methods. The roof control plan specifies the minimum support requirements such as bolt spacing, length, and type that will be used to support the roof

and ribs of coal mine entries. The support design procedure for roof control plans is left open to the mine operator, allowing innovation and development of new technologies.

Current roof support technology makes use of rock reinforcement principles to improve the strength and stability of the rock through the installation of roof bolts. This type of support is called intrinsic support, because it is located within the rock mass, providing internal reinforcement. In some situations where it may be difficult to install intrinsic support or where excessive deformation is expected, external supports in the form of standing supports may be used.

During the early years of the application of intrinsic support systems, in-mine trials and the observational approach were used to determine support requirements (Mark, 2000). Limited support system analysis was conducted, typically using analytic equations based on beam theory (Fairhurst and Singh, 1974). Over the years significant improvements were made in the types of support units and the understanding of the interaction of the rock mass with the support units.

At present there is more than 50 years of experience of the application of intrinsic support systems in coal mines that forms the basis for support design. This experience is captured in many of the support rules found in the mining regulations and

published in MSHA guidelines. The NIOSH-developed Analysis of Roof Bolt Systems (ARBS) (Mark et al., 2001) is an example of a design approach based on a statistical analysis of successful and unsuccessful applications of support systems.

As a result of this wealth of empirical knowledge, the support system for a new mine can simply be based on a support system that was successfully implemented under similar conditions elsewhere. However, the reliance on empirical experience does have limitations. As new support technologies become available, mining techniques change, and as mining depths increase, the historical experience may no longer be applicable. This shortcoming can be solved by following an engineering approach to support design. The engineering approach makes predictions about the stability of a system through the analysis of the strength and expected loads that the system will be subjected to (Hoek et al., 2003). When considering a system that consists of brittle rock materials, bedding planes, rock joints, steel bolts, and resin grout, the stability analysis can become complex. As computational methods have become more efficient and affordable, numerical models are increasingly used to conduct the analysis of excavation stability in rock materials. There are many computational models commercially available that can assist in conducting these types of analysis. However, at present no single engineering-based analysis method has found wide acceptance in U.S. coal mines (Mark, 2000; Tadolini et al., 2006).

3. DEVELOPMENT AND VALIDATION OF THE STRENGTH REDUCTION METHOD FOR ROOF SUPPORT DESIGN

The need for a standardized method to conduct engineering analysis of coal mine roof support systems has been addressed by making use of numerical models that are able to realistically simulate the rock mass response to excavations and the interaction of the support systems with the rock mass. The FLAC3D finite difference code (Itasca, 2014) was selected to conduct the model analyses. The modeling approach allows a “stability factor” (SF) to be determined for a supported entry. The SF is determined by using a modeling technique known as the strength reduction method (SRM) (Zienkiewicz et al., 1975). The SRM has a long history in numerical modeling and has often been applied in rock slope stability engineering to determine the safety factor of rock slopes (Lorig and Varona, 2000), but has not been widely used for underground excavation analyses. The classic SRM approach was adapted and modified to allow the

estimation of coal mine entry stability factors (Esterhuizen, 2012).

3.1 Applying the strength reduction method

The numerical models of coal mine entries simulate a slice perpendicular to the axis of the entry. The thickness of the slice is equal to the support row spacing, typically 1.2 m. The various rock layers are modelled with appropriate strength parameters. The contacts between various units of rock in the roof are modelled as discrete interfaces. The bedded rock within each unit is modelled as a layered material, using the ubiquitous joint material type available in FLAC3D. Support units are also modelled explicitly. The FLAC3D software has the capability to realistically model grouted steel supports, with or without pretension.

The SRM is applied by first conducting a stability analysis using average rock strength properties. Depending on the outcome, the analysis is repeated using either a decreased or increased rock mass strength until the point of collapse is satisfactorily bracketed. Strength adjustments are achieved by simultaneously reducing or increasing the cohesion, tensile strength, and the coefficient of friction of the rock mass. The stability factor is simply calculated as the inverse of the strength adjustment factor at the point of collapse of the modeled excavation. For example, if collapse occurs when the strength is reduced by a factor of 0.8, the stability factor would be 1.25.

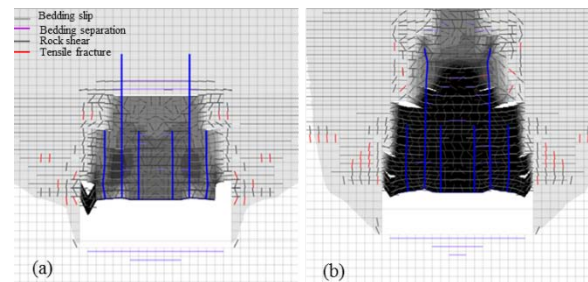


Figure 1: Model results showing a supported entry: a) when the rock strength has been reduced to a point of critical stability, and b) when further reduction of the rock strength causes roof collapse.

The occurrence of collapse is indicated by the inability of the model to reach a state of equilibrium after an extended number of solution cycles. Usually, this means that a section of the roof is accelerating downwards and equilibrium could not be reached. Figure 1(a) shows a plot of a numerical model of an entry in which the rock strength has been reduced to the critical point where collapse is about to occur. Figure 1(b) shows how the roof collapses when the rock strength is reduced by a further 5%.

When applying the SRM to underground coal mine excavations, it was found that floor heave was sometimes the mode of ultimate instability. This would occur if the floor rocks are weaker than the roof rocks. All analyses were therefore conducted by only reducing the rock mass strength above the roof of the excavation while leaving the coal and floor rocks unadjusted. Analyses may be conducted in which the effect of floor instability is assessed.

3.2 Model validation

The outcome of the modeling procedures was validated against empirical design methods that are used in US coal mines (Esterhuizen et al., 2014). The model results were initially assessed to determine if they are able to capture variations in roof stability predicted by the coal mine roof rating (CMRR) (Molinda and Mark, 1996; Mark et al. 2002). Additional verification was conducted by comparing SRM-calculated stability factors to the empirically based ARBS method (Mark, 2000; Mark et al., 2001). The CMRR and ARBS methods are based on extensive observation of entry stability in operating mines, capturing decades of empirical experience of the authors. These empirical methods are used to evaluate potential stability or instability in operating coal mines and are suitable for validating the SRM calculated stability factors.

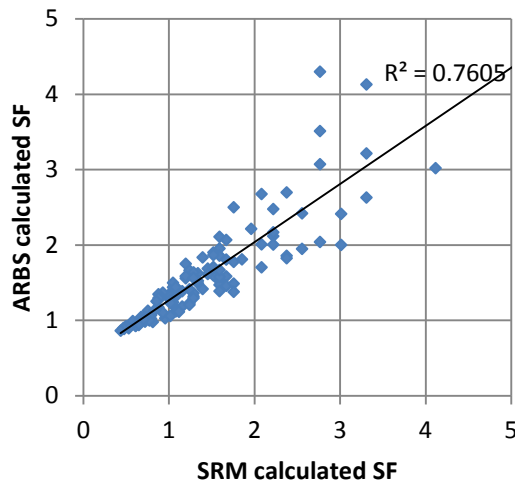


Figure 2: Comparison of stability factors calculated using the ARBS empirical method and the SRM for 120 cases of entries supported by 1.8-m bolts.

The relationship between SRM-calculated and ARBS-calculated SF values for the 120 models of entries supported by 1.8-m fully grouted bolts is shown in figure 2. The results show that the two methods predict similar trends, with a coefficient of determination of 0.76. At lower SF values the scatter of results is small, which is important for design.

The similarity of results achieved by the mechanics-based SRM and the statistically-based ARBS for this wide ranging set of conditions demonstrates that the SRM captures the essential factors affecting entry stability.

4. APPLICATION OF THE SRM TO EVALUATE SUPPORT ALTERNATIVES

The SRM has been applied to evaluate support systems for various operating coal mines. Two case histories are presented here in which support alternatives were evaluated to improve the understanding of the contribution of support elements to overall stability, and to quantify the degree of stability achieved.

4.1 Case history 1: Room-and-pillar mining with cable bolt support

Cable bolting is sometimes used as primary support in coal mines experiencing difficult roof conditions. In low-seam mines, the flexibility of the cable bolts allows greater length supports to be installed near the advancing face without the use of couplers. When used as primary support, the cables are typically installed in the same row as fully grouted bolts, replacing two or more of the bolts in each support row. A heavy steel channel may be used as a strap to spread the support load over a greater portion of the roof. Historically, MSHA has not allowed widespread use of partially grouted untensioned cable bolts for primary support.

At the case study mine, fully grouted rebar bolts with pre-tensioned cable bolts were used as primary support. It was found that when a large roof fall occurred, the cable bolts may be contained within the dome of fallen rock. As problematic roof conditions continued to exist, the mine management decided to modify the system using passive cable bolts as part of the primary support system. The cable bolts were located near the ribs of the entry, to increase the likelihood that they would be anchored outside the dome of potentially unstable roof. The modified system resulted in considerably improved stability conditions in the mine. However, the mine engineer was uncertain whether the modified system was indeed better than the original system for controlling the roof, or whether the improved conditions were related to changes in the geology or other factors. An analysis using the SRM was conducted to identify the differences between the two systems.

4.1.1 Geotechnical Conditions

The case study mine extracts the Lower Kittanning coalbed. The mine uses the room-and-pillar method in a mining height of about 1.2 m. The depth of cover is approximately 120 to 150 m. In

certain locations the roof consists of 10-m-thick laminated dark gray silty shale that is associated with difficult ground conditions. It is overlain by a stronger interbedded sandstone and shale unit. Observations of the rock exposed in roof falls show that it tends to delaminate in thin slabs that are about 2 to 6 cm thick, as shown in Figure 3. The uniaxial compressive strength of the intact shale is 55 to 60 MPa. The available rock strength and bedding information were used to classify the rock mass using the coal mine roof rating (CMRR) (Molinda and Mark, 1996). The CMRR classification of the silty shale roof is estimated at 45.



Figure 3: Typical roof fall showing laminated nature of the silty shale roof rocks and steep-sided collapse cavity.

Stress measured in the vicinity of the mine shows results typical of Northern Appalachia with a relatively high pre-mining horizontal stress associated with regional tectonic loading (Mark and Gadde, 2008; Dolinar, 2003). The major horizontal stress is estimated to be oriented at N80E. Where possible, the mining direction is oriented so that the development is directed favorably relative to the stress field.

4.1.2 Support systems analyzed

The original and modified support systems used at the mine were evaluated using the SRM approach. The support layouts are shown in figure 4.

The original support system consisted of fully grouted conventional bolts and tensioned cable bolts as part of the primary support, installed on-cycle.

Cable bolts are partially grouted, with 1.2 m of resin grout forming the anchorage zone. Each support row was installed through a heavy T3 channel. The first row of the pattern consisted of two, 1.8-m-long, No. 5 tensioned rebar bolts through the center section of the entry and two, 3.6-m-long, 15-mm-diameter cable bolts on the outside. The second row reverses the order. Bolt tension is nominally 5 t. The support rows are 1.2 m apart. Entries are 5.5 m wide.

The modified support system consisted of support rows with four 1.8-m-long No. 5 tensioned rebar bolts and two 3.6-m-long un-tensioned cables installed on a 4.3-m-long T3 channel. The cables are located about 50 cm from the ribs, near the extremities of the channel. Additionally, the entry width was reduced to 4.9 m.

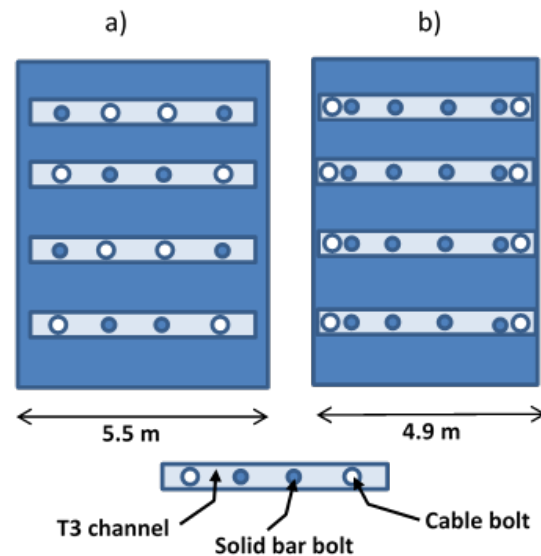


Figure 4: Support systems analyzed at case study 1 mine, showing a) the original system with tensioned cable bolts, and b) the modified system with passive cable bolts.

4.1.3 Results of SRM analysis

The original support system was simulated and the SF was determined to be 2.21. This SF value would be considered to be adequate for most room-and-pillar mining. However, the thinly laminated nature of the roof and relatively high horizontal stress appears to require a higher value of the SF to prevent large-scale roof falls. The modified system, using the greater intensity of fully grouted bolts and passive cable bolts produces a SF value of 2.84. This confirms that a significant increase in support capacity and stability is achieved by the modified system. The increase in stability can be attributed to both the increase in support and the reduction in entry width.

A closer look at the numerical modeling results showed that for the original system, instability occurs

when the roof yielding extends above the top of the cable bolts that are located near the center line of the entry. Under these conditions the cable bolts do not achieve their full load capacity, and collapse while encapsulated inside the failing roof. Under these conditions, the pretension does little to prevent the collapse.

With the alternative system, the location of the cable bolts outside the collapsing dome of rock helps to provide anchorage in the stable rock. In addition, the T3 channel is shown to act as a sling that holds the failing rock in position. The sling-action is able to control the roof over a much greater range of roof sag.

The results also showed that the fully grouted bolts would load up quickly as the roof sagged, but once roof failure developed above the bolts, the passive cable bolts would start to load up, acting almost like a tandem system that controls the roof after the fully grouted bolts started to shed load.

In practice it was found that the mine operational staff could readily identify areas which had sagged when using the modified support system. When this condition was observed, cribs or other types of standing supports were typically installed to arrest further movement. So although roof sag occasionally occurred, the support system was able to control the damaged roof, allowing remedial actions to be taken to prevent collapse.

4.2 Case history 2: Longwall Gateroad Support Changes

Longwall gateroads provide access to the working area of a longwall mine. The gateroads are subject to increased loading as the coal is extracted and loads are transferred to the adjacent unmined coal. Gateroads are expected to remain stable during these changing stress conditions. Gateroads are typically provided with primary support during development consisting of roof bolts. Secondary support in the form of cable bolts and screen may also be required to maintain the integrity of the roof rocks under the severe loading conditions near the longwall face.

At the second case history mine, fully grouted bolts are used as primary support and two additional bolts are installed at 45° in the rib-roof corner, as shown in figure 5. These bolts were originally intended to help support friable roof if stress-related roof damage occurs in the corners. However, as experience was gained it was found that the corner bolts did not appear to be required. In this case the mine management was interested to know if locating the corner bolts 30 cm away from the corner and

installing them vertically would improve the support efficiency.

4.2.1 Geotechnical Conditions

The mine also extracts the Lower Kittanning coalbed using the longwall mining method. The mining height is about 2.1 m and the depth of cover varies between about 150 m and 240 m. The roof rock is a sand shale with an average uniaxial compressive strength of 76 MPa. The CMRR for this roof rock is estimated to range between 47 and 52. The horizontal stress at this mine is expected to be typical of Northern Appalachian mines. Some stress-related roof-cutter formation was observed in the mine roof. The orientation of the longwall panels was optimized to minimize horizontal stress impacts.

4.2.2 Support Systems Analyzed

The support system evaluated consisted of 1.8-m-long fully grouted bolts with 180 kN capacity installed in rows 1.2 m apart. Each row consisted of four vertical bolts and two 45° angled bolts at the rib-roof corner. In addition, two supplementary cable bolts 3 m long were installed in rows 2.4 m apart. The cable bolts were installed on a T3 channel. The entry width is 4.9 m.

This support system was evaluated with corner bolts installed at 45° and with corner bolts installed vertically, located 30 cm from the entry ribs.

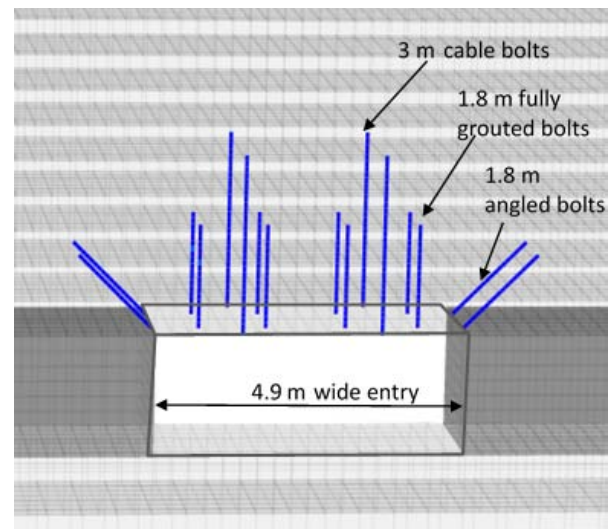


Figure 5: Central portion of a numerical model showing entry and support types evaluated.

4.2.3 Modeling results

The modeled SF against roof collapse for the base case, with the 45° corner bolts, was determined to be 1.85. Inspection of the bolt loading in the model showed that the corner bolts did not attract much load as the roof sagged. The load in the corner bolts only

increased to about 40 kN while the vertical bolts would load up to about 200 kN, which is their ultimate capacity. The cable bolts loading was more gradual, owing to the free length of about 1.8 m. Cable bolts approached their ultimate load after about 150 mm of roof sag.

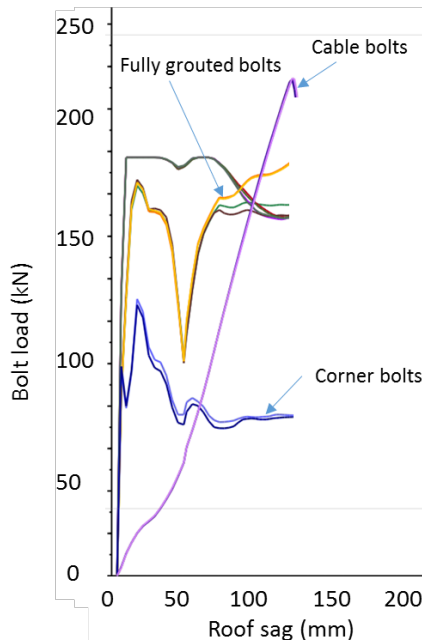


Figure 6: Bolt loads vs. roof sag for the support system in which the corner bolts are installed vertically.

When the corner bolts were located 30 cm from the rib and installed vertically, they attracted loads of up to 130 kN, and maintained a load of about 80 kN as the roof sagged. Figure 6 shows the bolt loads and roof sag for a case in which the rock strength has been reduced to the point of critical stability. The vertical corner bolts clearly contribute more significantly to the overall stability of the roof. The calculated SF was increased to 2.25 by the change in corner bolt location and orientation.

With this configuration, the cable bolts are able to control the roof sag up to about 130 mm when load shedding starts to occur.

These results provided confirmation that the 45° corner bolts were not as effective in contributing to the overall stability of the entry roof, and that the adjusted support system was likely to be more effective.

5. CONCLUSIONS

A numerical modeling approach has been developed that allows the stability factor of supported coal mine entries to be estimated. The numerical models have been calibrated against field-measured rock mass response and support interaction. The

model outputs can be evaluated further to determine the contribution of individual support elements to overall stability.

Two case histories demonstrate the application of the method to assessing support alternatives at operating mines. The calculation of a stability factor allows direct comparison of the overall efficiency of each support alternative.

Insight was also gained into the mechanics of the support-rock interaction, showing how the fully grouted supports are initially loaded-up, followed by loading of the passive cable bolts.

The studies demonstrate that numerical model-based analysis of coal mine entry support systems allows support alternatives to be evaluated and improves understanding of support element contributions. The optimized support systems provide improved safety for mine workers.

6. DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company name, product, or software does not constitute endorsement by NIOSH.

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