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Rapid assessment of roof stability in coal mine entries based on the outcome of validated numerical models

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ABSTRACT: Appropriately designed support systems are required to control potentially unstable ground around entries in coal mines. Alternative support systems can be evaluated using various approaches, including empirically based methods and advanced numerical models. However, conducting numerical model analyses can be time consuming, requires special software, and requires specialist expertise for setting up models and evaluating the results. In this study, the need for a more rapid method of assessing support alternatives is addressed. A regression-based equation has been developed based on the output of more than 600 numerical model analyses that investigated entry stability in various ground conditions, depths of cover, stress conditions, and support systems that might be encountered in US coal mines. The model outputs were verified against actual performance of coal mine excavations in a variety of geotechnical settings. Least squares curve fitting procedures were used to find the unknown parameters of a nonlinear equation that includes parameters for the rock mass strength, support characteristics, and geometric layout of the excavation and support system. The developed equation can satisfactorily predict the numerical model calculated stability factors. This allows practitioners to rapidly assess support alternatives for a range of conditions using spreadsheet software.

1. INTRODUCTION

Ground falls remain a significant factor in underground coal mine injuries and fatalities. In 2013 ground falls accounted for 4 of the 14 fatalities and 166 of the 1577 reported lost-time injuries in underground coal mines [1]. The stability of underground coal mine excavations is improved by the provision of support systems that control potentially unstable ground. Support systems may consist of rock reinforcement such as rock bolts and cable bolts and may be supplemented by standing supports such as engineered wooden cribs or cement-based columns. The design of appropriate support systems is complex because of the variable nature of the rock mass and the difficulty of estimating the interaction between the rock mass and the installed support system. Over the past 25 years multiple design approaches have been used in coal mine ground control. The approaches include empirical mechanistic methods, empirical statistical analysis, and rules of thumb and numerical methods, after Hebblewhite [2]. Of these approaches, numerical methods are increasingly used to supplement empirically based designs.

Improved numerical modelling procedures have recently been developed to assist in the design of support for coal mine entries [3]. The procedures make use of a modelling technique called the Strength Reduction Method (SRM) that allows calculation of a 'Stability Factor' against the collapse of the roof of a supported entry. In this case collapse is defined as a roof fall that extends more than 90 cm (3 ft) above the roof line of the entry. Small-scale skin-type failures or block-type failures associated with individual slips or joints are not considered.

The models are created using the FLAC3D finite difference code [4]. Details of the model layout and input selection are described in Esterhuizen et al. [5]. The models simulate a two dimensional slice through an entry. The thickness of the slice is equal to the bolt row spacing. The model boundary conditions were defined so that a repeating array of entries and intervening pillars was effectively modelled. Model calibration and validation studies were conducted to ensure that the developed modelling technique provides realistic estimates of the stability of mine entries. As part of the validation studies, model-calculated stability factors were compared to the results of the empirically based Analysis of Roof Bolt Systems (ARBS) method [6]. Outcomes of the validation studies are presented by Esterhuizen et al. [7, 8].

Despite these improved procedures, developing appropriate numerical models of the rock mass and support systems can be time consuming and requires familiarity with specialized software. To address this problem, support design engineers involved in day-to-day mining operations need procedures to rapidly assess support alternatives or the impact of changing geological conditions. This paper describes a simplified assessment method that is based on regression analysis of the results of a large number of numerical model analyses of support systems in coal mine entries. The resulting regression equation adequately predicts the outcome of the numerical model analyses. The equation can be implemented in a simple spreadsheet type program, allowing practicing engineers to rapidly assess support alternatives based on the outcome of the more advanced numerical models.

2. GEOTECHNICAL SCENARIOS MODELLED FOR EQUATION DEVELOPMENT

Numerical models using the SRM were used to evaluate a large number of geotechnical scenarios, representing a variety of depths of cover, field stress conditions, geological settings, and support systems that are used in US coal mines. The ranges of parameter values may be summarized as follows:

- Depth of cover: 100 m (330 ft) to 600 m (1960 ft)
- CMRR [8] based unit rating of roof units: 35 to 60
- Horizontal tectonic strain: 0.0002 to 0.0006
- Fully grouted bolt lengths: 1.8 m (6 ft) and 2.4 m (8 ft)
- Cable bolts lengths: 3.6 and 4.9 m with 260 kN (30 t) and 380 kN (40t) capacity
- Entry widths: 4.8 m (15 ft) to 10.2 m (33 ft)

Initially about 450 combinations of the variable parameters were modelled and SF values were obtained for each model. Additional models were created to clarify specific questions that arose during the analysis of the results. For example, 120 models were created to better understand the effect of strong beds within and above the bolted horizon. Models were also created to investigate the effect of weak overlying strata on support performance. Each geological scenario was evaluated up to sixty times, by modelling it in three different horizontal stress fields, five different depths of cover, and four different support systems. A total of 670 numerical models were ultimately evaluated.

2.1. *Numerical Modeling Results*

The numerical model results were insightful for understanding the complex interaction between rock response and support performance. It was possible to clearly identify the contribution of each support type to the overall stability of the excavation. It was also possible to obtain a better understanding of how stress is redistributed in the roof of an entry and how failure initiates and progresses until a collapse of the roof is initiated. Figure 1 shows an example of the failure modes around an entry that is at the point of collapse. The results show, for example, that the rock has failed beyond the top of the fully grouted bolts. Most of the load is being carried by the longer cable bolts. The challenge was to develop an equation that will replicate this seemingly complex interaction of the rock and the support system. However, careful examination of the model results showed that most of the model responses could be explained by considering the initial strength of the rock units, the horizontal stress within the units, and the presence or absence of weak or strong beds within or above the bolted horizon. The importance of the location of weak and strong layers was originally identified through field observations by Molinda and Mark [8] during the development of the CMRR and was also evident in the modelling results.

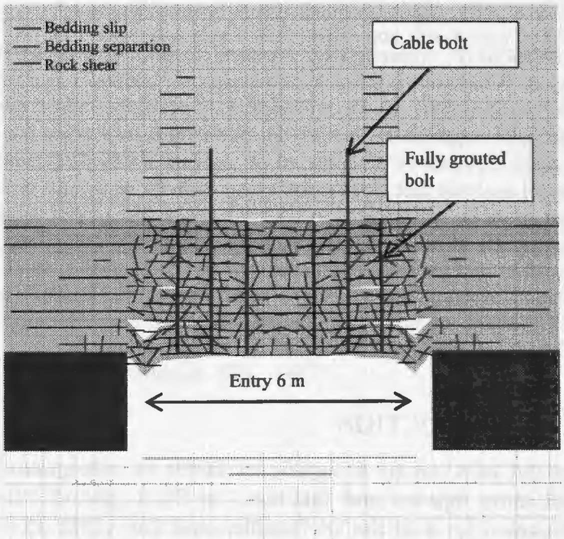


Figure 1. Example of a model result showing failure development in the immediate roof. The shorter bolts are contained within the failed rock while the cable bolts are providing suspension from the upper stronger roof beds.

3. EQUATION TO ESTIMATE ROOF STABILITY FACTORS

The SF results of the 670 numerical models were copied to a spreadsheet together with the key input variables for regression analysis. Initially a linear multiple regression analysis was conducted. The multiple regression results helped to identify the critical parameter inputs required to predict the SF of a supported entry. During the review of the results, it was found that non-linear relationships existed between some of the parameters and the calculated SF values. The prediction capability was improved by developing a non-linear equation to calculate the SF. Least squares error analysis was conducted to optimize the equation parameters using the generalized reduced gradient (GRG) solver routine available in the Microsoft Excel 2013 spreadsheet software. The final prediction equation was developed based on the FLAC3D calculated SF values of less than 3.0. This range was selected because critical SF values for design range from about 1.5 to 2.5 to ensure that maximum accuracy of prediction would be achieved in this range. There were 549 cases with SF values less than 3.0. For cases with SF values above 3.0 the estimation errors are slightly larger, but have little consequence, since the likelihood of instability is extremely low for these large SF values.

During the development of the SF estimation equation, groups of results that showed large estimation errors were identified and the reason for the large errors was sought. If necessary, additional model analyses were conducted to investigate the potential reason for the errors. For example, the influence of weak beds and strong beds in the entry roof was investigated in this manner and parameters were introduced to account for their presence. The final form of the SF estimation equation has three components, representing the self-supporting capacity of the immediate roof rocks, the primary support efficiency, and the secondary support efficiency. It was decided to express these parameters as a sum of the individual contributions so that the SF of an unsupported entry could also be estimated. This allows the contribution of the support system to roof stability to be quantified separately from the self-supporting capacity provided by the rock strength. The equation is as follows:

$$SF = SSC + PSE + SSE \qquad (1)$$

where:

SSC = Self-supporting capacity of immediate roof
PSE = Primary support efficiency
SSE = Secondary support efficiency

The development of the equation and the reasoning behind each component are described below. In the equations listed below all the constant terms were determined by the least squares error equation solving process.

In all the support calculations it is assumed that the support units have adequate strength and anchorage capacity to carry the dead weight of the rock within the supported horizon. The bolt and cable bolt capacity should therefore be checked beforehand.

3.1. *Self-supporting capacity*

Evaluation of the model results showed that the self-supporting capacity of an unsupported entry is affected by the strength of the immediate roof rocks, the horizontal stress in the roof, and any surcharge caused by weaker rocks above the immediate roof. The unsupported immediate roof is defined as the first 90 cm (3 ft) of roof rocks above the entry roof line. The self-supporting capacity (*SSC*) of the immediate roof is calculated as follows:

$$SSC = 15.20\left(\frac{SFIM \times SURIM^{0.290}}{W^{1.04} \times D^{0.287}}\right)^{0.832} \qquad (2)$$

where:

SFIM= Thickness-weighted average stability factor of the immediate roof units
SURIM = Surcharge factor to account for presence of weak beds above the immediate roof
W = Width of entry (m)
D = Depth of cover (m)

The thickness-weighted average stability factor of the roof units *SFIM* is calculated from the stability factor of each of the individual rock units in the immediate roof. The stability factor of each individual unit is calculated as the ratio of the rock mass uniaxial compressive strength to the pre-mining horizontal stress in the unit. The rock mass uniaxial compressive strength is estimated through rock mass classification, using the CMRR-based [8] unit ratings. The suggested procedure for estimating rock mass strength from the CMRR unit ratings is given in Esterhuizen et al. [5].

The immediate roof surcharge factor *SURIM* is simply the ratio of the strength of upper roof rocks to the strength of the immediate roof rocks. The upper roof is defined as 2.4 m (8 ft) above the immediate roof—that is, the roof rocks extending from 0.9 m (3 ft) to 3.3 m (11 ft) above the entry roof line. The surcharge factor has a maximum value of 1.0, which occurs when the immediate roof and upper roof are of equal strength. The thickness-weighted average strength is used in this and all strength calculations described below.

3.2. *Primary Support Efficiency*

The primary support efficiency (PSE) was found to be affected by the inherent stability of the reinforced rock within the bolted horizon and the length and spacing of the supports. It was also found that the presence of a strong bed within the upper half of the bolted horizon would provide extra stability. These observations from the modeling results are confirmed by similar field observations made by Molinda and Mark [8] during the development of the CMRR method and which are also included in the CMRR calculation as adjustments. The PSE is calculated as follows:

$$PSE = 0.020(PSI \times SFRR^{0.895} \times SBF^{0.096})^{1.440} \qquad (3)$$

where:

PSI = Primary support intensity, which represents the amount of primary supports per area
SFRR = Thickness-weighted average stability factor of reinforced rock units within the bolted horizon

SBF = Strong bed factor, to account for the presence of strong units in the upper half of the bolted horizon

The primary support intensity (PSI) is calculated as follows:

$$PSI = \frac{NB \times LB^{2.59}}{BS \times W} \tag{4}$$

where:
NB = Number of installed bolts in a row
LB = Length of the bolts (m)
BS = Bolt row spacing (m)
W = Entry width (m)

The stability factor of the reinforced rock units *SFRR* is again calculated as the ratio of the rock mass uniaxial compressive strength to pre-mining horizontal stress in each rock unit, similar to *SFIM*.

The strong bed factor *SBF* is calculated by comparing the rock strength in the upper 60 cm (2 ft) of the bolted horizon to the weighted average strength of the rock in the bolted horizon. It was apparent from the modeling results that a strong bed has an additional strengthening effect if it provides suspension capability to the primary supports. It was further seen that the strong bed thickness was significant because it is required to span across the width of the entry to provide suspension capacity to the supports. A thickness adjustment was therefore introduced for strong beds that are less than 2.4 m (8 ft) thick. The *SBF* is calculated as follows:

$$SBF = 1 + \left(\left(\frac{UCSMA}{UCSMB} - 1 \right) \times \frac{SBT}{2.4} \right) \tag{5}$$

where:
UCSMA = Thickness-weighted average rock mass UCS in the anchorage zone (MPa)
UCSMB = Thickness-weighted average rock mass UCS in the bolted horizon (MPa)
SBT = Strong bed thickness (m)

The *SBF* is limited to a minimum value of 1.0 and the strong bed thickness (*SBT*) is limited to a maximum of 2.4 m. In addition, the *SBT* is set to zero if the anchorage zone is intersected by more than one rock unit because the 60-cm anchorage zone is required to be fully located in a single strong-rock unit for the strong bed effect to be applicable. This requirement may be conservative, but is justified by the fact that variable roof sag between two relatively strong units could degrade the quality of the grout bond.

3.3. Secondary Support Efficiency

Secondary support analyzed in the models was always in the form of cable bolts that are partially grouted. The grout length was typically 1.2 m (4 ft) with the remainder of the bolt being free and is fixed by a bearing plate to the entry roof. The cable bolts were assumed to have about 5 tons of pretension. The cable bolts were supplementary to the primary supports, and were never evaluated as the only support system. The secondary support efficiency *SSE* parameter is therefore only applicable for cable bolts used in the manner described here. The equation for the SSE is as follows:

$$SSE = 0.283\ (SSI \times SFCA^{1.472})^{0.770} \tag{6}$$

where:
SSI = Secondary support intensity
SFCA = Thickness-weighted average stability factor of the rock in the cable bolt anchorage zone.

One notable difference between the primary and secondary support efficiency parameters is that the SSE does not contain a parameter for ‘rock reinforcement’ like the *SFRR* parameter for primary support. This parameter was found to be unnecessary because the length of grout is typically less than 30% of the cable bolt length and does not provide a significant reinforcement component as a fully grouted bolt would.

The secondary support intensity is calculated similarly to the PSI value using this equation:

$$\mathrm{SSI} = \frac{\mathrm{NC} \times \mathrm{LC}^{1.16}}{\mathrm{CS} \times \mathrm{W}} \tag{7}$$

where:
NC = Number of installed cable bolts in a row
LC = Length of the cable bolts (m)
CS = Cable bolt row spacing (m)
W = Entry width (m)

SFCA is the thickness-weighted average SF of the rocks in the cable grout anchorage zone. This zone is typically 1.2 m (4 ft) or greater in length. The *SFCA* is calculated using the same procedure as described above for *SFIM* of the immediate roof.

3.4. Discussion

All the parameters in the equations described above can readily be calculated by a spreadsheet type program, if the thickness and unit rating data of each roof unit are provided. A spreadsheet application makes it a simple matter to conduct sensitivity analyses and quickly assess support alternatives or the impact of changes in geology.

4. PERFORMANCE OF THE PREDICTION EQUATION

Shown in Figure 2 is the correlation between SF values calculated by the nonlinear equation and the FLAC3D numerical models of the 549 entries that have SF values of less than 3.0. The standard error was calculated to be 0.25, which represents a coefficient of variation of 16.9%. The coefficient of determination is 0.85 as shown in Figure 2.

The quality of the match between the equation predicted and FLAC3D calculated SF values is affected by the seemingly erratic rock mass response to small changes in input parameters. This can be ascribed to the strain softening rock mass that was modelled, in which the response can change dramatically for a small change in input values.

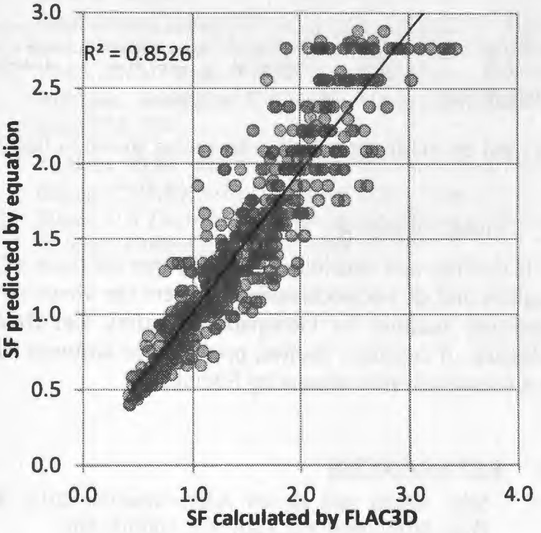
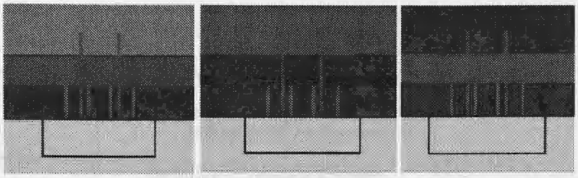


Figure 2. Comparison of SF values calculated by FLAC3D and predicted by the prediction equation for the 549 cases in which the FLAC3D calculated SF was less than 3.0.

The ability of the prediction equation to estimate FLAC3D calculated SF values is demonstrated by considering the three geological scenarios presented in Figure 3. The figure indicates increasing rock strength by lighter background shading. Supports consisting of 1.8-m (6-ft) long fully grouted bolts and 4.8-m (16-ft) long cable bolts are also shown. The rock unit strengths had CMRR-based unit ratings that varied between 33 and 45. Note that the 1.8-m (6-ft) bolts are fully located in a relatively weak rock unit. The models were evaluated at a depth of cover of 200 m (650 ft). Three horizontal stress scenarios were assessed. The first simulates a low horizontal stress scenario that might be encountered in Western US coal mines. The second is a moderate horizontal stress typical of the mid-continent coal mines, and the third represents a relatively high horizontal stress condition that may be found in the eastern US coal mines.



a) Geology G1: Roof strength increases upwards

b) Geology G2: Weak bed above fully grouted bolts

c) Geology G3: Strong bed in roof strata

Figure 3. Diagrams showing vertical sections through three entries evaluated to demonstrate the ability of the prediction equation to estimate FLAC3D results. Geologic layering is indicated as well as one of the support systems considered. Fully grouted bolts are indicated in blue and cable bolts in red.

Figure 4 shows how the calculated SF values vary as the depth, rock mass quality, and support type change. The ability of the nonlinear equation to track these variations is also shown. Note how the equation successfully predicts the considerable SF increase associated with geology G1 in the low horizontal stress scenario. Also, the SF of the unsupported entry doubles from about 0.5 to 1.0 as the horizontal stress becomes more favorable. The 1.8-m (6-ft) long bolts are shown to have very little impact on stability because they are fully located within the lower weak rock unit. Given the complex nature of the problem being investigated, the performance of the nonlinear prediction equation is considered to be very satisfactory.

5. CONCLUSIONS

The results of 670 numerical models were used to develop a nonlinear prediction equation that can be used to assess the SF of the roof of a supported entry in coal mines. The SF represents the stability of the roof against potential collapse that could extend more than 90 cm (3 ft) above the roof line of the entry. The prediction equation provides similar SF results to those that would be obtained through advanced numerical model analysis.

Parameters for the equation were developed by reviewing empirical design approaches, current design approaches, and numerical model outputs. The final form of the prediction equation was determined through least squares error analysis of numerical model determined SF values.

The prediction equation is valid for entries in bedded rocks supported by fully grouted primary supports and partially grouted cable bolts as secondary support. The numerical models forming the basis for developing the equation did not consider entries supported by cable bolts alone and should not be used to model cable bolts without primary supports.

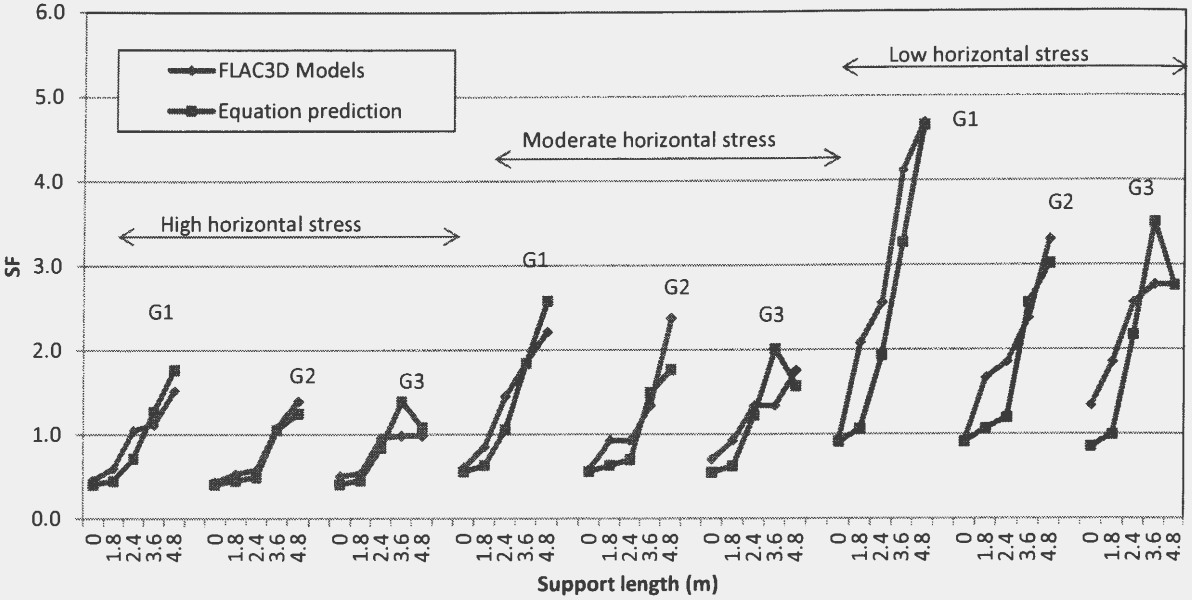


Figure 4. Example showing SF values calculated by FLAC3D models and the prediction equation for entries shown in figure 3. Unsupported entries are shown by zero support length.

It is assumed that the support units have sufficient capacity to carry the dead weight of the rock within the supported horizon. Support capacity should therefore be checked beforehand.

The developed nonlinear equation is simple to calculate and can easily be incorporated into a spreadsheet type analysis. The stability factors predicted by the nonlinear equation are sufficiently accurate for the rapid assessment of support alternatives during the initial stages of entry support design. The equation can also be used to verify existing designs, without the need to conduct full numerical model analyses.

The SF prediction equation should only be used as an assessment tool to assist in the design and engineering analysis of proposed support systems.

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