AN INTEGRATED APPROACH TO SUPPORT DESIGN IN UNDERGROUND COAL MINES

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ABSTRACT

Rock mass classification systems are extremely useful for site characterization and have been employed by the rock mechanics community for several decades. While empirical in nature, the classification systems provide a viable means to quantify the nature of rock mass, which is necessary for stability analyses. In U.S. coal mines, the Coal Mine Roof Rating (CMRR) is the most widely used classification system for several purposes, including support selection, chain pillar design, assessing the stability of extended face cuts, etc. The Analysis of Roof Bolt Systems (ARBS) is an empirical method developed from the CMRR to guide selection of roof bolts as the primary support system in U.S. coal mines. In this paper, the experience of Peabody Energy in applying ARBS to support design is discussed. In general, data from the Peabody mines show that ARBS predictions match well with field conditions. Peabody, however, does not use ARBS as the stand-alone methodology for support selection. Peabody uses a two-pronged approach in which the support requirement is initially estimated from the classification method, and then numerical modeling is used to select the proper reinforcement system. Such an integrated approach is necessary, as ARBS suggests only the "amount of steel" that may be used to support the roof and does not specify which type of roof bolt to use. A case study is used to demonstrate the usefulness of ARBS and Peabody's integrated approach to support design. Also, the application of ARBS at several Peabody mines showed a very good correlation with support cost. The correlation indicated a direct relation between bolting cost and the ARBS value.

INTRODUCTION

A rock mass is an extremely complex material to deal with quantitatively. This is further so when one attempts to describe its "quality" in relation to its engineering behavior. Several factors influence rock mass behavior, including the number, nature, and spatial distribution of discontinuities traversing through it; compressive strength of the rock matrix; presence of water; etc. Despite the complexity, efforts have been made to provide quantitative descriptions of rock mass quality, which are indispensable for engineering analyses.

During the past 4 decades, significant progress has been made in quantitative rock mass site characterization, especially through the development of rock mass classification systems. The most notable of these systems are Bieniawski's [1973] Rock Mass Rating (RMR) and the Rock Mass Quality Index (Q) proposed by Barton et al. [1974]. Common to these and other classification systems is the selection of a few significant variables that have the most bearing on rock mass engineering behavior. Each of these variables are assigned numerical values that reflect their importance in controlling such behavior. After individual ratings are assigned to the significant parameters, they are mathematically manipulated to obtain one final number, which provides a quantitative description of the nature of the rock mass.

Both the RMR and Q were developed mainly based on case histories from tunnels driven in "hard rock." As a result, they cannot be directly extended for use with coal measure rocks, as the parameters that influence the response of the rock mass are different. Several classification schemes applicable for coal measure rocks have been developed by various researchers, the most popular of which is the Coal Mine Roof Rating (CMRR) developed by the U.S. Bureau of Mines [Molinda and Mark 1994]. This system follows Bieniawski's RMR format with values ranging from 0 to 100 to indicate the quality of the strata. The CMRR is most widely used in the United States and Australia; it has also been employed in South Africa, Canada, and the United Kingdom. The most recent of the coal mine classification systems is the Coal Measure Classification (CMC) proposed by Whittles et al. [2007].

Over the years since its inception, the CMRR has been used for several purposes in coal mine strata control. Correlations have been developed to select roof bolts as the primary support system, in sizing longwall chain pillars, to forecast if extended face cuts will work or not, and several others [Mark and Molinda 2005]. The main interest of this paper is the usefulness of the CMRR and its offshoot, the Analysis of Roof Bolt Systems (ARBS) [Mark et al. 2001], for roof bolt design as they are applied to Peabody Energy mines. Also, the limitations of ARBS are pointed out, and the integrated approach that Peabody has developed to overcome some of the problems is discussed.

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THE COAL MINE ROOF RATING (CMRR)

The CMRR has two different versions: field [Molinda and Mark 1994] and drill core [Mark et al. 2002]. The field CMRR is estimated from underground observations where the roof is exposed mainly by roof falls and overcasts. Since visual observations play a key role in the field CMRR, it is somewhat subjective. Two different persons are likely to come up with different field CMRR values for the same site, although experience has shown that they will usually differ by no more than about five points. In contrast, drill core CMRR is derived from laboratory-determined parameters and measurements on cores, which are less subjective, but are subject to their own variability.

In both the field and drill core CMRR, the following parameters are weighed to estimate the roof competence:

- Compressive strength
- Discontinuities

In the field CMRR, the discontinuities are characterized by their cohesion, roughness, spacing, and persistence. In the core version, discontinuity ratings are determined by the fracture spacing and diametral point load strength.

The process of computing CMRR starts by dividing the roof into structural "units." Strength and discontinuity ratings are then determined and added together to calculate the "unit ratings." The unit ratings are then corrected for the number of discontinuity sets and the moisture sensitivity. Next, the overall CMRR of the roof is obtained by thickness-weighted averaging of the unit ratings within the "bolted interval." Adjustments are then applied to the average CMRR for the following factors to determine the final rating:

- Strong bed in the bolted interval
- Number of units
- Groundwater
- Overlying beds

The structure of the CMRR as given above seems to work well in quantifying the quality of roof for most situations. One important assumption in the development of the CMRR is that the bedding plane is the major discontinuity in a coal mine. Since bedding planes are almost always horizontal to subhorizontal, their orientation is not a key factor in determining the roof stability. This is the reason why the orientation of a discontinuity has not been accounted for in the CMRR. The presence of other discontinuities, such as slickensides, is considered in the CMRR, but the orientation of those features is not.

There are situations, however, where practical experience indicates that the orientation of these features may be a critical factor in determining the support requirements, as indicated by the rock fall shown in Figure 1. This photo was taken at a mine that has frequently occurring slickensided slip planes, which intersect at unfavorable angles to create wedge failure conditions. The immediate roof at the mine is made of black shale overlain by a very competent limestone. The CMRR for this roof was estimated to be over 60. Despite this high CMRR, several rock falls have occurred at the mine mainly because of the unfavorably oriented slickensided slip planes.

Figure 1.—Roof fall initiated by unfavorably oriented slip planes.

In cases like these, a discontinuity orientation adjustment to the CMRR can help to make it more general. This additional correction, however, is not essential for every application. It may be applied only if the instability is governed by the orientation of the discontinuity and occurs very frequently in a panel to make it a "general" feature rather than an isolated abnormality. Further, the correction is needed only if it is intended to deal with any instability originating from the discontinuity orientation by the primary support system. Even though several possibilities exist theoretically, practical experience in coal mines indicates that orientation-related rock falls are unlikely unless multiple features intersect at adverse angles. Based on the experience at the one case history mentioned above, the tentative suggestion in Table 1 is made to account for the discontinuity orientation in the CMRR. The adjustment shall be applied only to the unit ratings of the units that are intersected by the discontinuities.

Table 1.—Adjustment in the CMRR for the unfavorable discontinuity orientation

Condition	CMRR adjustment
Multiple discontinuities (joints, slip planes, etc.) intersecting at adverse angles to create sliding or wedge failure conditions	–5

ROOF BOLT DESIGN USING ARBS AND THE CMRR

One of the most important applications of the CMRR is to design roof bolts as the primary support system. This is accomplished through an empirical approach called the ARBS [Mark et al. 2001]. Roof fall rates from 37 U.S. coal mines formed the necessary database for the logistic regression analyses conducted in ARBS. The final guidelines help in the selection of roof bolt pattern, bolt length, and intersection span based on the CMRR and other geomining inputs. ARBS is valid, however, only if the bolts work in beam building or supplementary support mode. A discriminant equation in terms of depth and CMRR was developed to determine which support mechanism was applicable for a given mining condition [Mark et al. 2001]. In ARBS, the required bolt density is given by a parameter, $PRSUP_G$, as given below:

$$PSUP_G = (SF)\,[0.3\,(Is_G - Is)]\,[(5.7\log_{10} H) - (0.35\,CMRR) + 6.5] \qquad (1)$$

where SF = stability factor,
Is_G = suggested intersection span, ft,
Is = actual intersection span, ft,
H = depth of cover, ft,
and CMRR = coal mine roof rating.

The key advantages of ARBS are that it is simple to use and it is based on actual case histories. Therefore, a large number of uncertainties associated with coal mine ground control designs are inherently included in the statistical analyses conducted for ARBS. However, just like any other empirical tool, ARBS has its own limitations. First, the design equations cannot be extrapolated with confidence beyond the range of the original data. Second, some critical equations were developed from rather limited amount of data and thus should be used with caution. Third, and most importantly, ARBS does not specify which type of bolt to use in providing the bolt density given by Equation 1.

In U.S. coal mines, several different types of roof bolts are used, and each one works on a different mechanism [Dolinar and Bhatt 2000]. For example, the reinforcing action in fully grouted bolts is different from resin-assisted mechanical bolts. Unfortunately, the selection of bolt type is an extremely complex problem that cannot be addressed by a simple approach like ARBS. For this reason, Peabody uses an integrated approach wherein the support requirement is first estimated by ARBS, then the bolt type is chosen with the help of numerical modeling.

In the following sections, Peabody's experience with the application of ARBS and details on the Integrated Support Design Methodology (ISDM) are presented.

PEABODY EXPERIENCE

Roof bolt design at most Peabody mines has evolved over the years by trial and error and limited engineering studies. Bolt pattern, bolt type, entry width, etc., were changed until each operation found the best system that worked for its conditions. Therefore, this database would form a very reliable check on the validity of the CMRR and ARBS. Data have now been collected from several operating Peabody mines located throughout the major U.S. coalfields. The number and location of the mines covered in this study are listed in Table 2. Some details relevant to the estimation of the CMRR and ARBS for the studied mines are provided in Table 3. The data were collected from both the mains and the panels at each operation. In the areas of adverse roof conditions, some secondary supports were also installed. The number of MSHA-reportable roof falls per 10,000 ft of development was collected from the mines that had noticed some instability. The data are given in Table 4 and plotted in Figure 2 against the CMRR. Five mines, with CMRR values ranging from less than 30 to nearly 50, have experienced roof fall rates less than 0.2 per 10,000 ft of development. The roof fall rates at three other mines were significantly higher.

Table 2.—Number of mines by coalfield used in the study

Coalfield/State	No. of mines
Interior Province: Eastern Region (Illinois Basin)	8
Appalachian	4
Colorado	1

Table 3.—Different variables relevant to the CMRR and ARBS at the case study mines

Depth, ft	150–1,400
Entry width, ft	16–22
Actual intersection span, ft	27–35
Steel grade, ksi	40, 50, 60, 75
No. of bolts per row	3–6
Bolt row spacing, ft	3.5–5
Bolt length, ft	3.5–10
Bolt diameter, in	0.625–0.875
Bolt type	RAM, FGR, TT
Accessories	Wood boards, square steel plates, straps, and wire mesh

RAM = resin-assisted mechanical. FGR = fully grouted rebar. TT = torque tension.

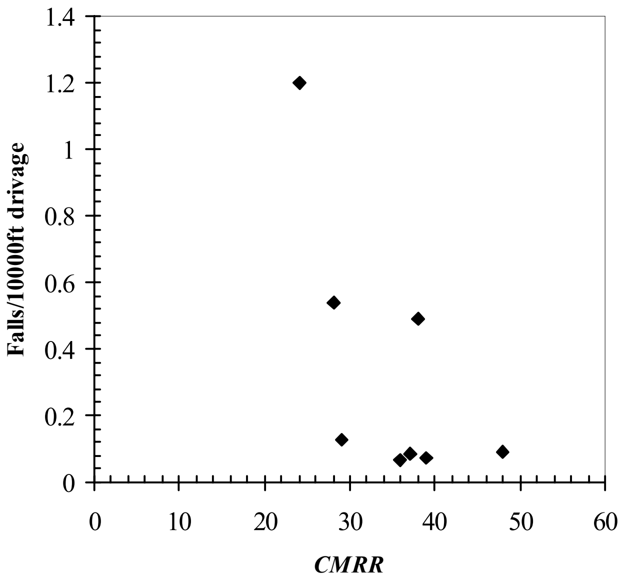

Figure 2.—Roof fall rate against CMRR for some case study mines.

At each of the studied operations, the CMRR was estimated from either underground observations or drill core data. Then, the suggested ARBS from Equation 1 was computed and compared with the actual value based on the successful roof bolting system. In estimating the suggested ARBS value, the stability factor was set to 1.0 in Equation 1. The derived numbers are given in Table 4 and plotted in Figure 3.

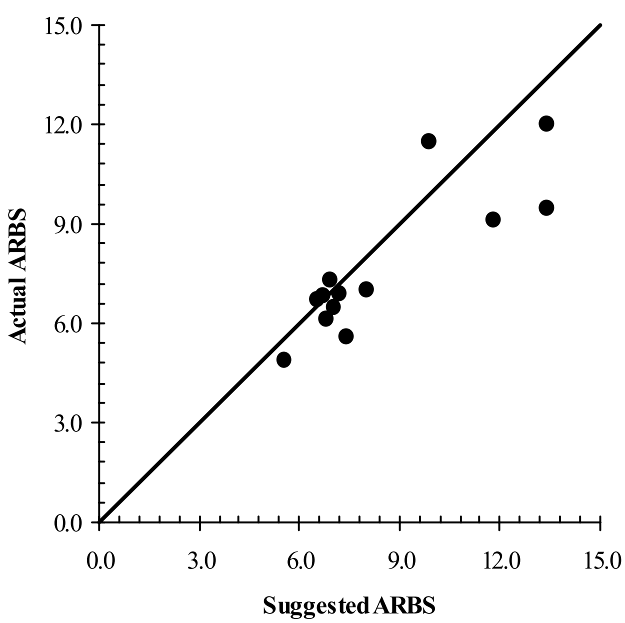

Figure 3.—Suggested versus actual ARBS values at the case study mines.

Table 4.—Suggested and actual ARBS values at the case study mines

Mine	CMRR	Suggested ARBS	Actual ARBS	Actual-to-suggested ARBS ratio	No. of roof falls per 10,000 ft of development
A.....	39	5.6	4.9	0.88	0.074
B.....	37	7.1	6.5	0.92	0.082
C	40	6.5	6.7	1.03	—
D	40	6.8	6.1	0.89	—
E.....	38	7.4	5.6	0.75	0.490
F.....	28	11.8	9.1	0.77	0.540
G	24	13.4	9.5	0.71	1.200
H	36	7.2	6.9	0.96	0.069
I......	29	13.4	12.0	0.90	0.130
J	44	8.0	7.0	0.88	—
K.....	48	6.7	6.8	1.01	0.089
L	46	7.0	7.3	1.05	—
M	43	9.9	11.5	1.16	—

The data in Table 4 show that the CMRR values at the studied mines varied from 24 to 48. Further analysis indicated that all eight Illinois Basin mines had CMRR values equal to or below 40, while all of the Appalachian mines, except one from the northern Appalachian coalfields, had CMRR values that exceeded 40.

Table 4 and Figure 3 further show that, in general, there is excellent agreement between the suggested and actual ARBS values at the studied mines. The three mines (E, F, and G) with the lowest ARBS stability factors also have the highest roof fall rates. These data support the validity and usefulness of ARBS in predicting the primary support requirements.

Since ARBS is an indirect measure of the amount of steel installed for roof support, it is logical to expect a good correlation with the support cost. To verify this, data

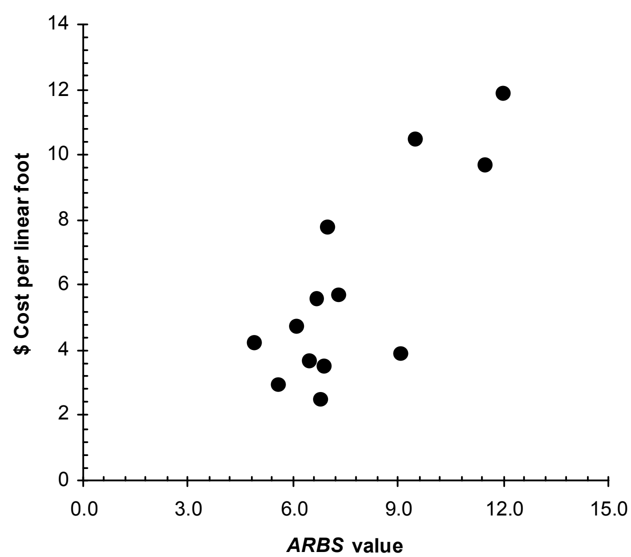

Figure 4.—Relation between the ARBS value and the average cost per linear foot of advance over a 6-month period.

were collected from the same mines in Table 4, which are plotted in Figure 4. A direct linear relation between ARBS value and the support cost can be seen from this figure. Note that the cost shown is the average value for a 6-month period for each mine and includes only the steel (bolt + plate) used for the primary support. This analysis shows that ARBS will also serve as an indicator of the support cost incurred in installing the bolt density suggested by it.

INTEGRATED SUPPORT DESIGN METHODOLOGY (ISDM)

Within the confines of the original database, discussions in the preceding section have shown the effectiveness of ARBS in estimating the required support density. For complete roof bolt design, however, it is also necessary to know which type of bolt to use for any given mining conditions. While providing the same support resistance, different types of bolts will provide different levels of reinforcement depending on how harmonious the bolt type is with the roof conditions. Any incompatibility may lead to instability or uneconomic designs.

Unfortunately, no scientific guidelines exist that help determine the matching bolt type for a given roof. The best available alternative is to use numerical modeling wherein the specific geomining conditions are simulated with different types of bolts to determine the best one. Therefore, a very effective roof bolt design can be achieved by combining the positive aspects of ARBS with those of numerical modeling. In fact, achieving such a fusion is the essence of Peabody's Integrated Support Design Methodology (ISDM). The individual steps in this process are shown in Figure 5. With some site-specific alterations, this methodology is being implemented in all of the new support design exercises at Peabody mines.

The ISDM process clearly recognizes the intractability of strata control designs by any single approach. The ISDM aims to maximize the benefits of empirical and analytical methods, neither of which alone can provide answers to all of the questions in support design. As Figure 5 indicates, one of the most critical elements of the

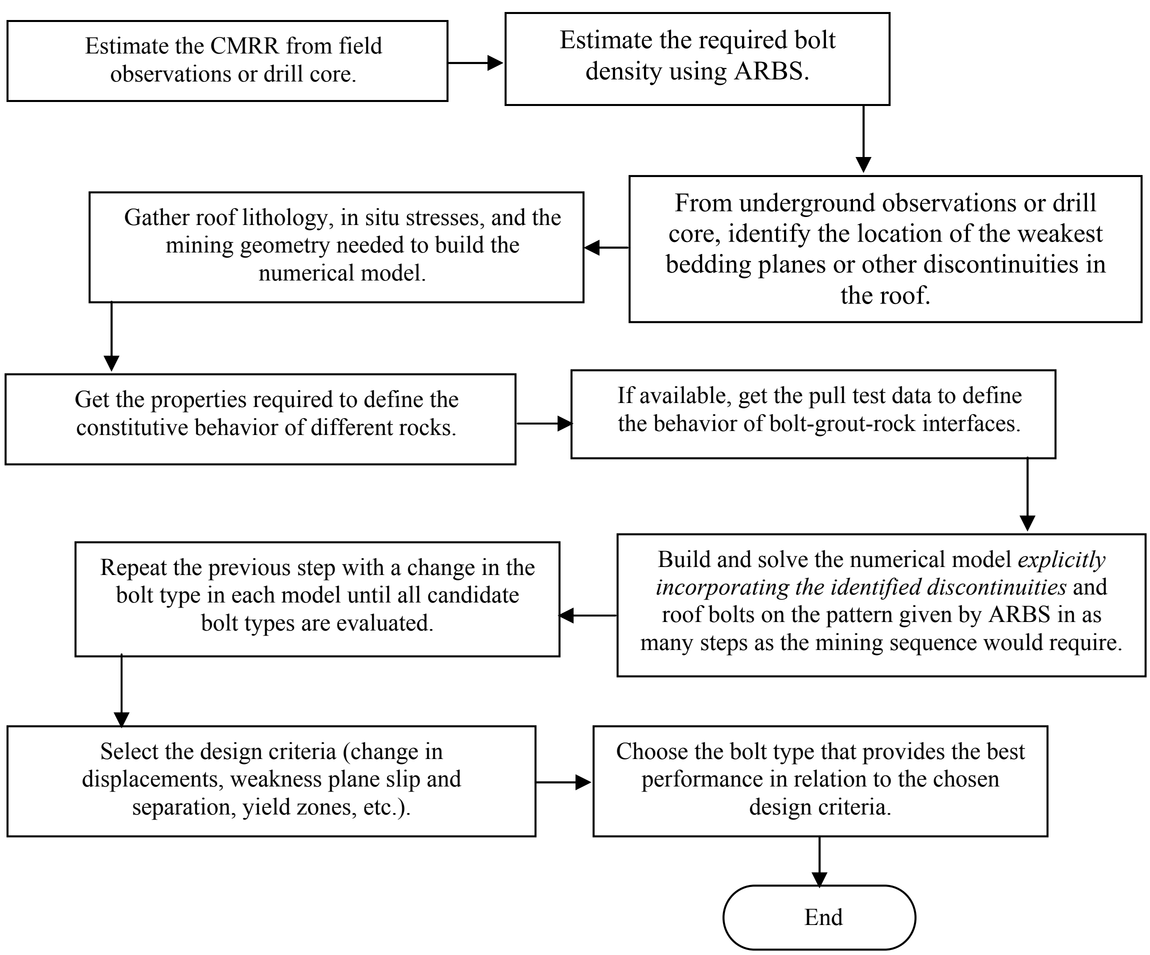

Figure 5.—Individual steps in Peabody's ISDM.

ISDM is to identify the weakest bedding planes in the roof and explicitly include those features in numerical models. Such detailed analysis is not possible any other way but through numerical modeling. Also, different types of roof bolts could easily be simulated with numerical methods. More details on the individual steps in Figure 5 are provided below with the help of a recent support design exercise carried out for a Peabody mine.

ISDM EXAMPLE

The mine in this case study will extract a coal seam of variable thickness with a final mining height of about 7 ft. The immediate roof at the mine is predominantly shale. At a few places, where the coal seam is thicker than 7 ft, a rider coal forms the immediate roof. Although over the bulk of the reserve the bolted horizon consists mainly of shale, at a few locations sandstone comes close enough to the seam to be a part of the bolting horizon. The average depth of the seam is about 680 ft. Exploratory drill core was available from 11 boreholes with all of the necessary rock strength information to estimate the CMRR.

The following discussion illustrates each step involved in arriving at the recommended support design using the ISDM:

Step 1: Estimate the CMRR.

From the available 11 core holes, the CMRR was estimated and the numbers are shown in Figure 6.

Step 2: Use ARBS to determine the required bolt density.

Since the CMRR is reasonably consistent (as seen from Figure 6), the average value of 41 was used as the input for ARBS. Based on this and other mining inputs, it was found that for the proposed 18-ft-wide entry at the mine, four 6-ft-long #6, grade 60 bolts on 3.5-ft row spacing will provide a stability factor of 1.25. Since this bolt pattern will provide a stability factor in excess of the one recommended in ARBS, the design has been accepted. It may be mentioned that this is just one of the several support patterns suggested for different geomining conditions at the study mine.

Step 3: Gather necessary inputs for modeling.

The next step in ISDM is to conduct numerical modeling to determine the proper bolt type. Based on physical observations on the recovered cores, no major discontinuities other than bedding planes were discovered at the case study mine. Although core breakage was noticed at several locations, the only discontinuities considered for the modeling were those between distinct lithologic units or those that were not related to core handling. For instance, one hole that has been used for modeling has rider coal in the immediate roof and shale above it. From core

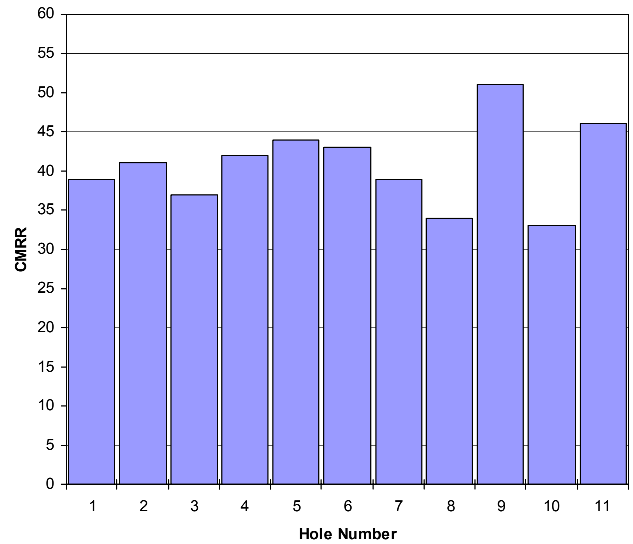

Figure 6.—CMRR variation at the case study mine.

examination, it was found that there were seven different weakness planes within the first 7 ft of the roof that need to be considered in the modeling. All these seven contacts were explicitly included in the models for this type of roof lithology.

In all of the models, the rock was treated as an elastic material. The necessary data required to define this constitutive behavior were available from laboratory testing on cores. The contacts, however, were simulated using inelastic Mohr-Coulomb behavior. Even though the bedding planes were not tested for their properties, the assumed numbers will not significantly alter the modeling outcome, as the objective here is to compare the relative performance of different types of bolts under otherwise identical conditions. Any errors in the input data will most likely affect all of the models to the same extent.

Since the case study mine is a new venture, field pull tests on roof bolts were not conducted to determine the required inputs for the bolt simulation. However, actual pull test data from a different mine on #6, grade 60 fully grouted rebar were used to estimate the shear stiffness of the bolt system.

Step 4: Build and solve the models with different bolt types.

Two different bolt types were considered for the case study mine: fully grouted and torque-tension type. In the case of the torque-tension bolt, only the top 4 ft was grouted. The models for each bolt type were run in two stages. In the first stage, the model was solved to create the premining stresses; in the second, the mine entries were created with bolts installed on the pattern suggested by ARBS. In each model, the bedding planes identified in step 3 were explicitly included.

In previous modeling studies reported in the literature, roof bolts were typically simulated in one of two ways: either the bolts were built "physically," or mathematically equivalent bolts were used. In the first approach, the roof bolt, resin, and drill hole are explicitly made in a numerical model. Inputs are then provided to define the constitutive behavior of each element separately along with the interface properties for bolt-resin and resin-rock contacts. Ideally, this seems to be the most accurate way to model roof bolts. Difficulties, however, arise for several reasons. First, the roof bolts are dimensionally two or three orders smaller than the mine entry and, therefore, achieving a proper mesh density becomes extremely difficult even with the best of the available computing resources. Second, the constitutive behavior of the bolt-resin and resin-rock interfaces has never been tested in situ to provide all of the inputs needed for modeling. Third, problems in numerical solutions will easily occur because of the several awkwardly intersecting contact planes in this approach. Finally, it is extremely time-consuming to build and solve a model that has all of the complications of "physically" including roof bolts. To make the problem solvable in a reasonable amount of time and within the limits of available computing resources, several assumptions and simplifications must be made. As a result, even though the explicit inclusion of bolts may provide a sense of precision, the benefits of such a tedious approach may be more illusory than real. In any case, explicit modeling of roof bolts may perhaps be justified for research work, but is certainly not a feasible option for routine support design.

In the second approach, mathematically equivalent roof bolt elements are created whose constitutive behavior will provide an accurate representation of the roof bolt action. Since many of the complications involved with the first approach are eliminated, it is much easier to model a large number of bolts in a single model with little effort. Also, the assumptions involved in formulating the bolt elements are probably no worse than those required to make physically built roof bolts "work" numerically. For the obvious advantages, in this study the second approach has been chosen for bolt modeling using a finite difference-based code, FLAC3D[4] [Itasca Consulting Group 2005]. This software is by far the most commonly used modeling tool in rock engineering. FLAC solves the dynamic equation of motion in time-domain to provide pseudostatic solutions. The explicit solution scheme adopted in FLAC3D makes it an ideal tool for simulating nonlinear behaviors [Itasca Consulting Group 2005].

Step 5: Examine the model results and choose the final bolt type.

Roof bolts are point-acting-type structures whose radius of influence is rather limited. As a result, there may not be a significant difference in the stress state of the

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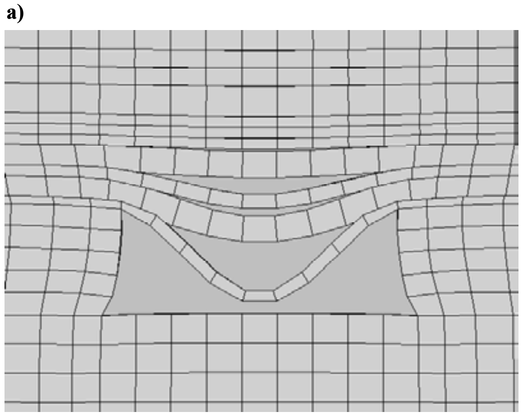

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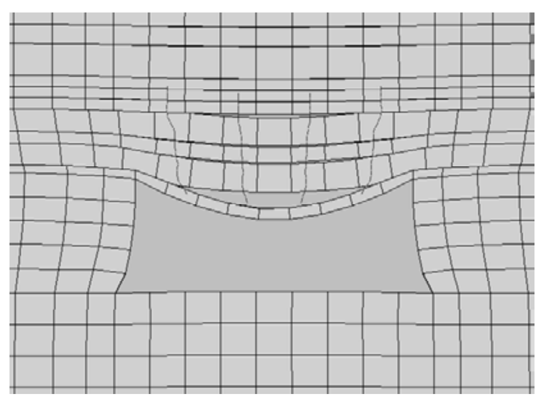

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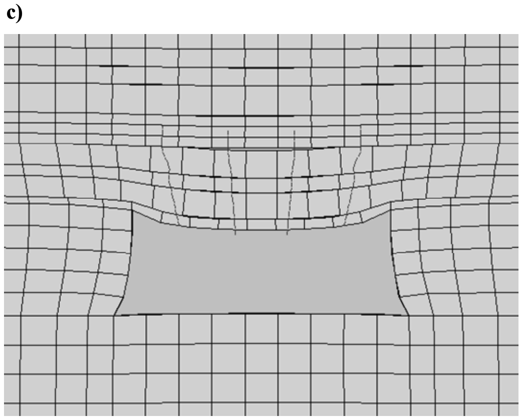

Figure 7.—Deformed geometry with (a) no bolts, (b) fully grouted bolts, and (c) torque-tension bolts (for comparison, deformations are exaggerated by 20 times in all three graphics).

[4] Fast Lagrangian Analysis of Continua in 3 Dimensions.

immediate roof to make a substantial difference to the extent of yield zones or to the magnitude of local safety factors. For this reason, in this study, the criterion used for bolt performance comparison was vertical displacement. If a bolt keeps individual layers in the immediate roof tightly bundled together, then the bolt will most likely perform well. Based on this criterion and the layered nature of the immediate roof, torque-tension rebar was found to be the best bolt type, as shown by the modeling results in Figures 7–8.

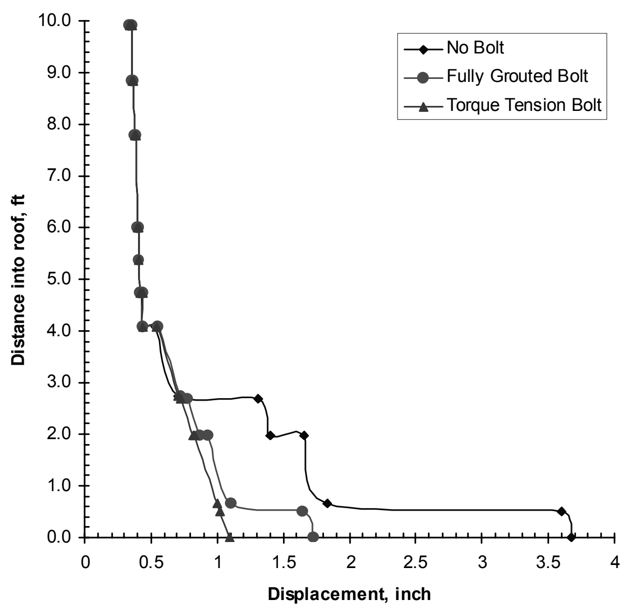

Figure 8.—Vertical displacement at the middle of the entry with distance into roof.

Without roof bolts, Figure 7 shows that the first three layers will separate from the layers above, and the resulting deformations are so large that these layers will most likely fail. Even with fully grouted roof bolts, the first layer's movement is considerable, and thus some skin failures cannot be ruled out. The torque-tension bolts, however, substantially reduce the separations and slips across the first three bedding planes. This can be seen more clearly from a plot of vertical displacement at the middle of the entry shown in Figure 8.

In a different part of the reserve at the case study mine, the immediate roof has shale and sandstone within the bolting horizon. By a similar numerical modeling exercise, the models found that fully grouted roof bolts could stabilize the roof as effectively as torque-tension bolts. For the obvious cost benefits, fully grouted bolts were recommended for this area.

CONCLUSIONS

Empiricism and coal mine strata control are inseparable. The contributions of empirical rock mass classification systems and their derivatives for successful roof support designs are considerable. Notwithstanding the ground-breaking advancements in numerical modeling, empirical tools will continue to play a critical role in strata control designs. This fact has been demonstrated by the success of the CMRR and ARBS, as shown in this paper.

Much can be achieved by synthesizing the benefits of empirical and analytical tools, which indeed is the crux of Peabody's ISDM. As demonstrated by the case study in this paper, this integrated approach can provide very detailed information on the performance of different types of roof bolts under the same roof conditions. Also, the modeling helps to explain the failure mechanics, and this knowledge will substantially aid in devising proper support measures.

REFERENCES

Barton N, Lien R, Lunde J [1974]. Engineering classification of rock masses for the design of tunnel support. Rock Mech *6*(4):189–236.

Bieniawski ZT [1973]. Engineering classification of jointed rock masses. Trans S Afr Inst Civ Eng *15*:335–344.

Dolinar DR, Bhatt SK [2000]. Trends in roof bolt application. In: Mark C, Dolinar DR, Tuchman RJ, Barczak TM, Signer SP, Wopat PF, eds. Proceedings: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000–151, IC 9453, pp. 43–51.

Itasca Consulting Group [2005]. Fast Lagrangian analysis of continua in 3 dimensions, version 3.0. Minneapolis, MN: Itasca Consulting Group, Inc.

Mark C, Molinda GM [2005]. The coal mine roof rating (CMRR): a decade of experience. Int J Coal Geol 64(1–2):85–103.

Mark C, Molinda GM, Barton TM [2002]. New developments with the coal mine roof rating. In: Peng SS, Mark C, Khair AW, Heasley KA, eds. Proceedings of the 21st International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 294–301.

Mark C, Molinda GM, Dolinar DR [2001]. Analysis of roof bolt systems. In: Peng SS, Mark C, Khair AW, eds. Proceedings of the 20th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 218–225.

Molinda GM, Mark C [1994]. Coal mine roof rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387.

Whittles DN, Reddish DJ, Lowndes IS [2007]. The development of a coal measure classification (CMC) and its use for prediction of geomechanical parameters. Int J Rock Mech Min Sci *44*(4):496–513.