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Using the coal mine roof rating (CMRR) to assess roof stability in U.S. coal mines

The stability of any underground opening is, in large part, a function of the strength of the rock mass which surrounds it. The Coal Mine Roof Rating (CMRR) has been developed to quantify the defects in the rock mass and compile a strength value which can be used for engineering design. The CMRR has been applied to a number of ground stability problems, including chain pillar design, roof bolt selection, hazard assessment, intersection design, and numerical modeling. The CMRR procedure and some of these applications are described in this paper. The CMRR will soon be available in a Visual Basic computer program, allowing easy integration into exploration programs and standard roof fall assessments.

Introduction

While overall safety in U.S. coal mines has improved dramatically in the last 50 years, fatality rates continue to exceed other major industrial sectors (fig. 1). Fatalities due to ground falls make up a significant portion of this rate. In 1998 there were 790 injuries and 13 fatalities due to falls of roof. These were reported from 827 underground mines producing 380 million tonnes of coal. In 1998, of 2,617 reportable falls, 30% resulted in injury or fatality (MSHA, 1998).

Longwall mining continues to be much safer than room and pillar mining. While longwall production is approaching the levels of room and pillar mining, the roof fall rate for room and pillar mining is significantly higher (Dolinar and Bhatt, 2000) (fig. 2). For this reason a number of the National Institute for Occupational Safety and Health (NIOSH) ground control research studies have concentrated on this area. Intersections are significantly more likely to fall than non-intersections. In 1996 over 71% of reported roof falls with known locations occurred in intersections, making them 8-10 times as likely to fall as other locations.

In the U.S., all unsupported roof is considered hazardous and it is illegal to travel under unsupported roof. Therefore, it is the failure of supported roof which contributes to the vast majority of injuries. A number of factors contribute to the failure of supported ground. These include: overspanned intersections, insufficient support, excess horizontal stress, multiple seam abutment loading, and undersized pillars. An element in many of these failures is weak geology. The accurate assessment of the strength of the rock mass is critical to the stability of the opening. Coal mine operators have always made an assessment of roof rock quality on some level. Usually the information is qualitative and obtained from roof exposure due to mining, or less reliably, from drill hole data. The information may be presented as a hazard map. Historically, accounts of mine roof geology have been highly descriptive and required interpretation for use in engineering design and support selection. More quantitative efforts at determining the roof strength have included rock tests like uniaxial compressive strength, the Brazillian indirect tensile test, direct shear, or triaxial tests. These tests suffer from small sample size but, more importantly, fail to measure the real rock weaknesses. Existing rock mass classifications have also been applied with limited success (RQD, RMR, URCS, Q system) (Molinda and Mark, 1994.).

The CMRR, developed by the Bureau of Mines in 1994, is now widely used for a variety of purposes including roof hazard assessment, chain pillar design, and stress modeling. The underlying philosophy of the CMRR is that it is not the strength of the intact rock fabric which makes a stable rock mass, but the defects or discontinuities which weaken or destroy the roof beam (Molinda and Mark, 1994). The CMRR is intended to evaluate the roof discontinuities which most contribute to the weakness and failure of the roof mass. The emphasis is on weak bedding planes, slickensides, joints, and laminations. As a result, the geologic origin of a discontinuity is less important than its engineering characteristics. The CMRR is designed to evaluate the inherent strength of the bolted interval and returns a number from 0-100, with 100 being absolutely solid roof.

The CMRR is a two-part system. First, the Unit Rating of each rock member in the bolted interval is determined by evaluating the discontinuities in the rock with simple field tests (fig. 3). A chisel is struck parallel to bedding to determine the tensile strength on bedding. A ball peen

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hammer is used to make an indentation scaled to the compressive strength of the rock matrix. Points are assigned for the spacing and frequency of bedding planes, joint sets, slickensides, and other discontinuities, with lower point values representing weak, closely spaced slickensides or laminations. Points are deducted for moisture sensitivity and

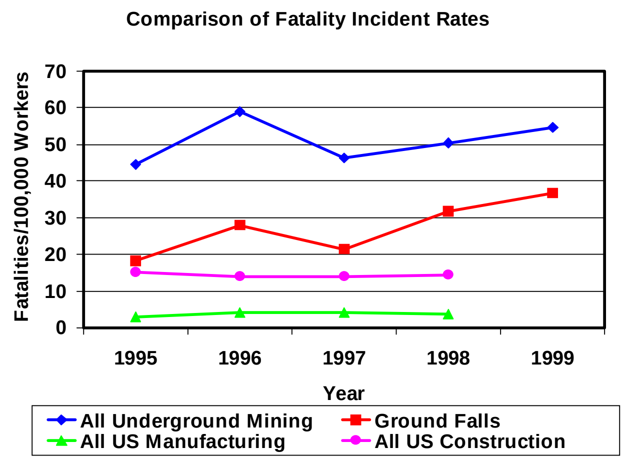

Fig. 1. Fatality rates of selected industries as compared to underground mining.

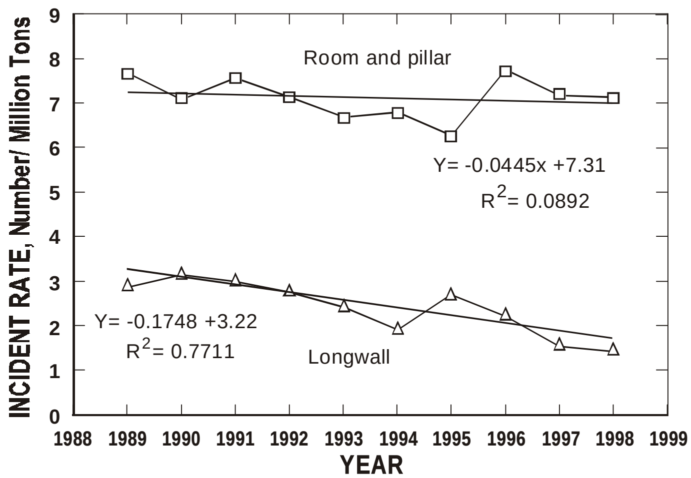

Fig. 2. Comparison of longwall and roo and pillar injury rates.

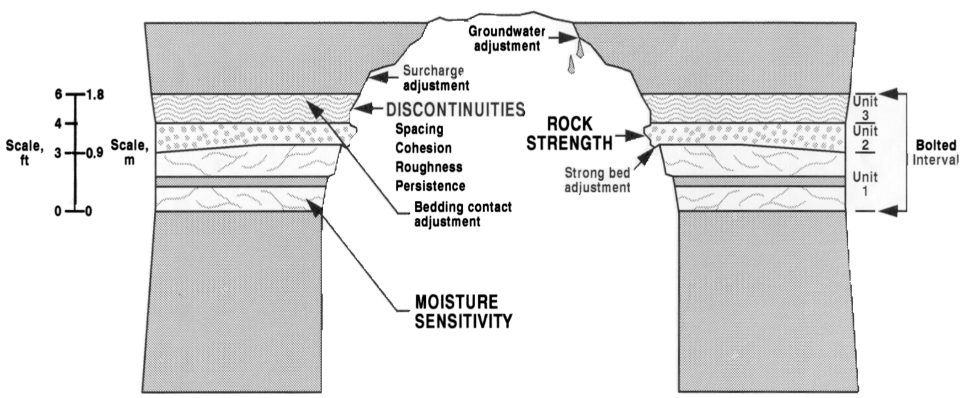

Fig. 3. Components of the coal mine roof rating (CMRR).

multiple discontinuities. As an example, a weak, slickensided, moisture-sensitive, fireclay with clod-like, disturbed bedding would likely have a Unit Rating = 29 (fig. 4). At the other end of the scale, a massive, crystalline, sandstone with faint, widely-spaced, cross bedding would have a Unit Rating = 77 (fig. 4).

The second part of the CMRR is the determination of the Roof Rating. The thickness-weighted average of the Unit Ratings is determined, and adjustments are made for Unit associations, including an addition of points for the presence of a strong bed in the bolted roof. One of the most important concepts incorporated into the CMRR is that of the strong bed. Through many years of experience with roof bolting throughout U.S., coalfields mine operators have found that the overall structural competence of bolted roof is very often determined by the quality of the most competent bed within the bolted interval. This fact was early recognized with mechanical bolts. Regulations of the U.S. Mine Safety and Health Administration at 30 CFR 75.204(f)(1) require that “roof bolts that provide support by suspending the roof from overlying stronger strata shall be long enough to anchor at least 0.3 m into the stronger strata”. In recognition of this importance an addition of points is applied when a strong roof unit at least 0.3m thick is present in the roof beam. The points increase with thicker, stronger units. Other features of the roof rating include a deduction for weak Unit contacts, and a deduction for groundwater inflow.

The working range of the CMRR is 25-100. When the CMRR is less than 25, the roof usually collapses immediately upon mining.

Originally designed to use roof falls and overcasts as sources of data input, the CMRR has since been adapted to be calculated from drill core (Mark and Molinda, 1996). This fulfills a need for calculating the CMRR in advance of mining for mine planning purposes. In the calculation for core both the compressive strength of the rock matrix and tensile strength of the bedding and discontinuity surfaces are measured by the point load test (IRSM, 1985) This proven rock test has been adapted to measure both axial and diametral (bedding) strength. A new conversion factor from point load index of strength ($I_{s(50)}$) to uniaxial compressive strength (UCS) has been determined from a large data base recently provided by a large U.S. coal company (Rusnak and Mark, 2000).

Applications of the CMRR

NIOSH has made extensive use of the CMRR as a research tool. In ground control investigations ranging from chain pillar design to intersection sizing, the CMRR has helped in developing remedies for roof failure. The CMRR has been most useful in comparing roof geologies from different regions. Figure

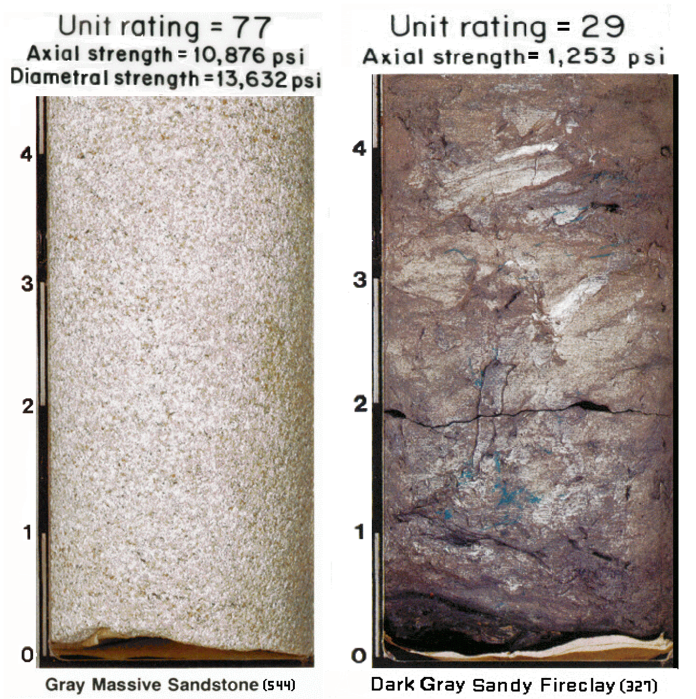

Fig. 4. Rock units with ferm number and rock strength
(1 mega pascal = 145 pounds/ft^2

5 shows the distribution of CMRR's collected from around the U.S. (Mark et al., 1994). The data reflects what is generally thought about roof strength: weaker, soft rocks, susceptible to horizontal stress are found in the northern Appalachian basin, and stronger, more massive sandrocks found in the southern Appalachian basin and in the Uinta basin in Utah. The interior basins in the U.S. generally have more carbonate sequences as they alternate between marine and terrestrial environments.

HAZARD MAPS

For many years, operators have been creating hazard maps which are usually contoured maps of drill hole data indicating the presence, thickness, or location above the seam of some hazardous rock type. For a clearer and more objective presentation, CMRR values can be and contoured in the same way. Figure 6 shows a CMRR map of a mine in eastern Ohio. Most of the mine roof is a strong sandstone (CMRR=76), but there are "shale pods" occurring in the roof which cause bad top. The worst is a lag deposit on the margin of a paleochannel which has caused numerous roof falls and very uneven roof due to failure before bolting and between bolts (CMRR=28). With practice the operator can begin to identify a potentially weak roof, which may be prone to different types of failure. Some roof may be unable to tolerate any sag at all or may be susceptible to horizontal stress. By correctly defining these zones and identifying their strength, via the CMRR, secondary support can be applied in an efficient way.

In a study at a mine in the Illinois basin, the typical roof consists of 1.0 m of shale (Unit Rating = 35) overlain by 0.4m of limestone (Unit Rating = 100). The CMRR of this sequence = 55. The roof fall rate = 0.27 roof falls/hectare of supported roof (Fig. 7). When the limestone thins to less than 0.3 m the CMRR drops to 44, and the roof fall rate increases to 1.53 roof falls/hectare (Fig. 8). The mine's bolting plan

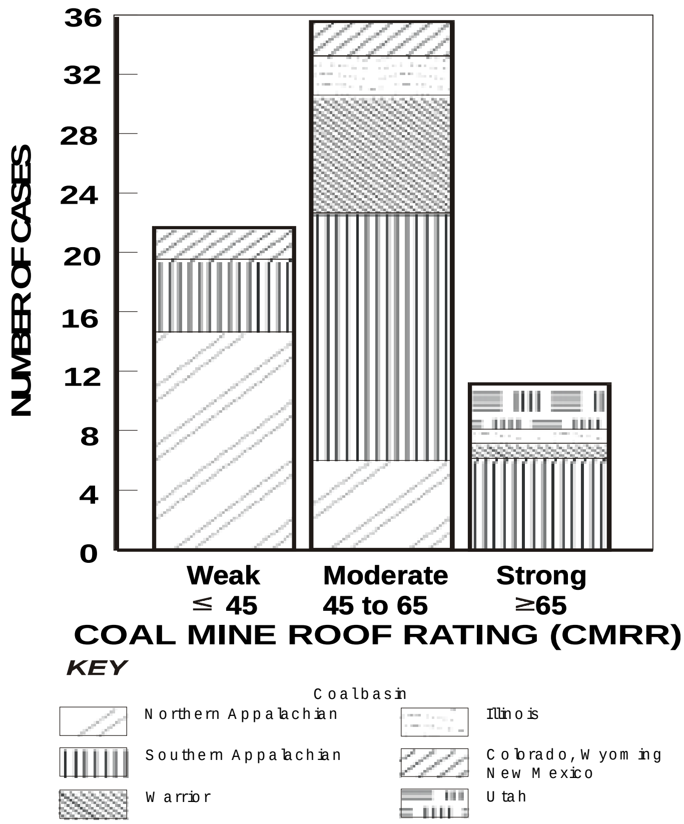

Fig. 5. Geographic distribution of CMRR measurements in the U.S.

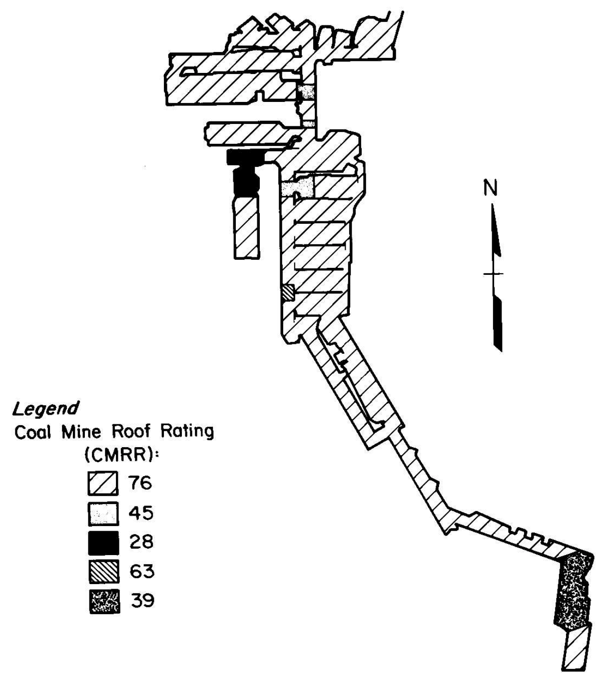

Fig. 6. Example of a CMRR map in one of the study mines.

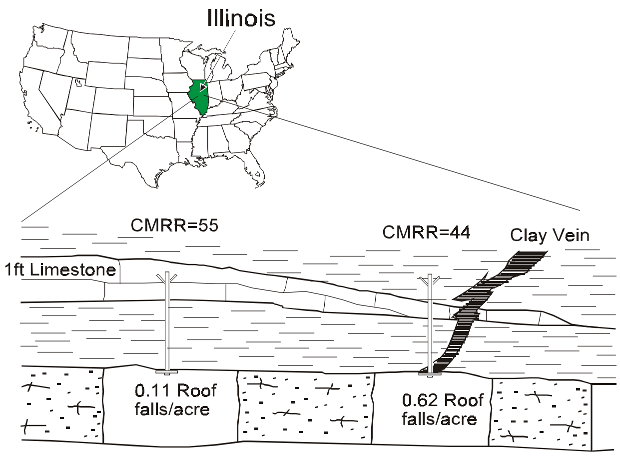

Fig. 7. Roof geology and its effect on roof falls in an Illinois coal mine
(1 acre = 0.405 hectare).

called for bolt anchorage at least 0.6 m above the limestone with a minimum 1.8 m long bolt when the limestone thinned to less than 0.3 m. Even with this plan the roof fall rate in the thin limestone was much higher than in the normal thicker limestone. One explanation is found in the presence of clay veins in the roof. When a large clay vein severed the limestone beam, limestone less than 0.3 m provided little residual support and failed more frequently.

EXTENDED CUTS:

Extended cuts (cuts greater than 6 m in length) are commonly used with remote control continuous miners. Extended cuts can greatly increase productivity, but they have been associated with a number of fatal roof fall accidents. When extended cuts are attempted in weak roof, the roof may collapse before it can be bolted, causing hazardous conditions. To help predict where conditions may not be suitable for extended cuts, data on the CMRR and extended cut experience were collected at 36 mines in 7 states (Mark, 1999). It was found that when the CMRR was greater than 55, deep cuts were routine in nearly every case. When the CMRR was less than 37, extended cuts were almost never taken. Between 38 and 55, extended cuts were feasible sometimes but not others. The data also show that extended cuts are less likely to be stable if either the entry span or the depth of cover increases (Fig. 9a and 9b).

ROOF BOLT SELECTION:

In an empirical study of 37 coal mines conducted throughout the U.S., a number of geotechnical parameters were documented in an effort to explain the performance of primary roof support. The factor that was most closely related to the roof fall rate was roof rock strength as measured by the CMRR. Figure 10 show that most of the moderate to high roof fall rate cases are concentrated below CMRR≤50. All cases of CMRR≤30 show moderate to high roof fall rates, and high roof fall rates are rare for cases of CMRR≥60. Intersection spans were also measured and figure 11 shows the relationship between intersection span and CMRR for high, moderate, and low roof fall rates. For intersections with CMRR≥50 and sized according to the equation line there were no cases of high roof fall rates. This line can be used to indicate whether smaller spans might be helpful in relieving the incidence of roof falls.

Roof bolting is mandatory for all coal mine excavations in the U.S. In the area of roof bolt selection, the CMRR is also useful. While no single bolt parameter showed a strong relationship with roof fall rate, a combination of variables expressed as an index of support density and capacity did. The following index variable was developed to represent 5 different bolt parameters.

$$PRSUP = \frac{L_b \bullet N_b \bullet C}{14.5 \bullet S_b \bullet W_e}$$

where:
L_b=Length of the bolt (m)
N_b=Number of bolts per row
C=Capacity (kN)
S_b=Spacing between rows of bolts (m)
We=Entry width (m)

Equations were also developed from the field data which show the relationship between CMRR and bolt density and capacity as represented by PRSUP.

The suggested value of PRSUP is determined as:
PRSUP=15.5-0.23 CMRR (low cover)
PRSUP=17.8-0.23 CMRR (high and moderate cover)

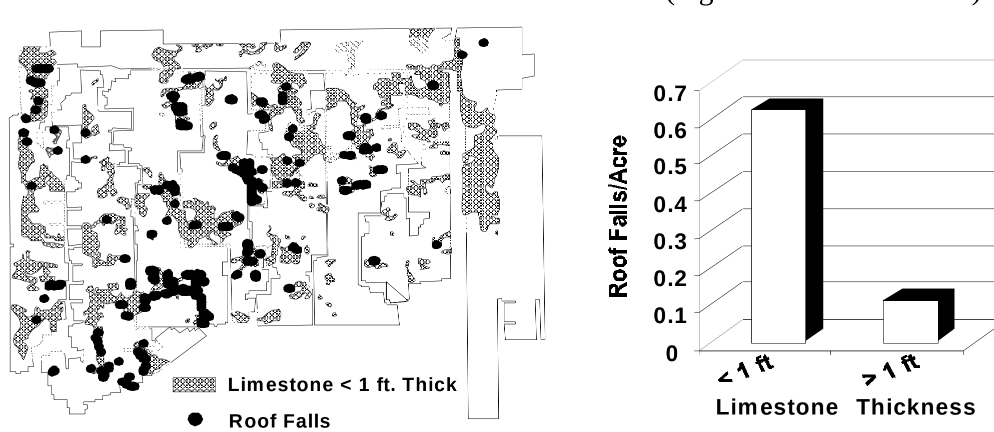

Fig. 8. Map of an Illinois mine showing limestone thickness and roof falls
(1 acre = 0.405 hectare and 1 metre = 3.28 ft).

Figure 12 shows these equations together with the field data from which they were derived. The design equations are slightly more conservative than the discriminate equations that they are based on. Bolt length selection also incorporates the CMRR (Mark, 2000)

LONGWALL PILLAR DESIGN:

The design of chain pillars for longwall mining has come a long way since the 1970's. Tailgate failures, once common, are now rare. Most of the gateroads in the U.S. are now designed using the Analysis of Longwall Pillar Stability (ALPS) procedure. As with other ground control issues, it is apparent that the strength or weakness of the roof rock will contribute to the stability of the opening. Today the roof rock strength as measured by the CMRR is fully integrated into the ALPS procedure to arrive at a safety factor which varies with the strength of the roof rock. Data was collected from 44 longwall mines producing 62 individual gateroad case histories for evaluation. The success or failure of each case was determined and discriminate analysis was used to determine which geotechnical variables were significant predictors of success or failure of the tailgate. Two variables, the ALPS safety factor and the CMRR were the most significant predictors. Figure 13 shows the relationship between CMRR and the ALPS safety factor. The success or failure of each tailgate case history was successfully predicted in 82% of the cases. That is, successful cases are well separated from failures based on the following regression equation:

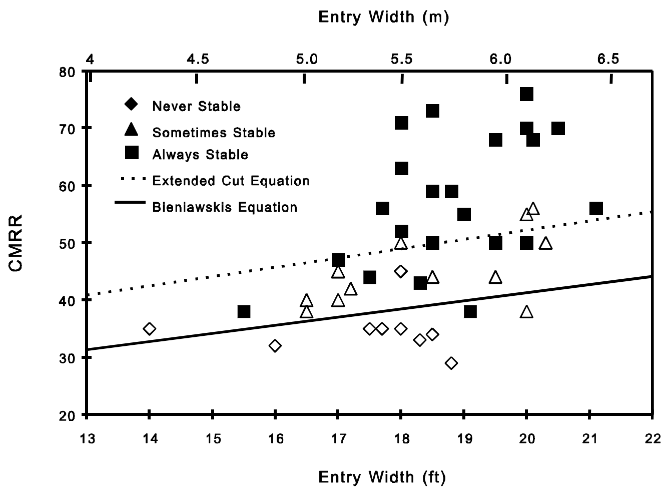

Fig. 9a. Relationship between CMRR and entry width for extended cur roof data.

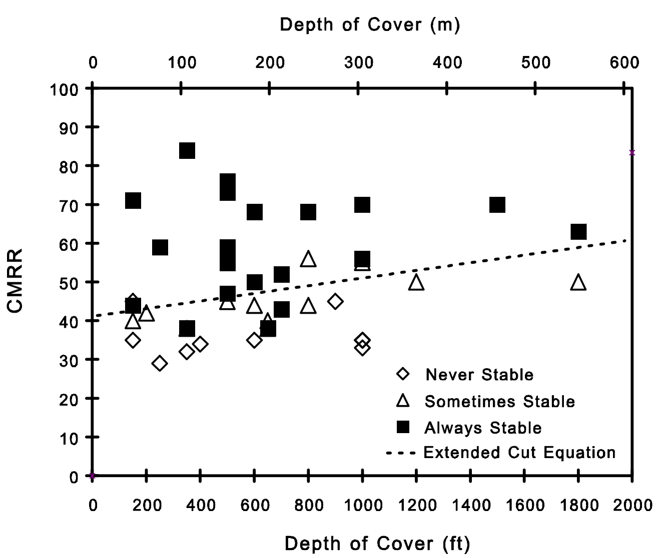

Fig. 9b. Relationship between CMRR and depth of cover for extended cut roof data.

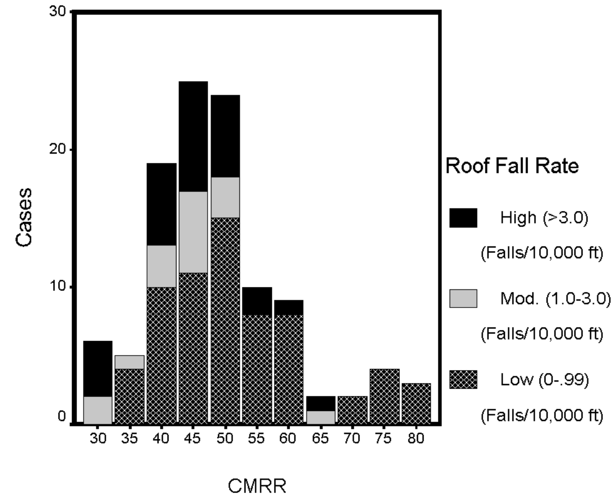

Fig. 10. Relationship between the CMRR and roof fall rate (1 metre = 3.28 ft).

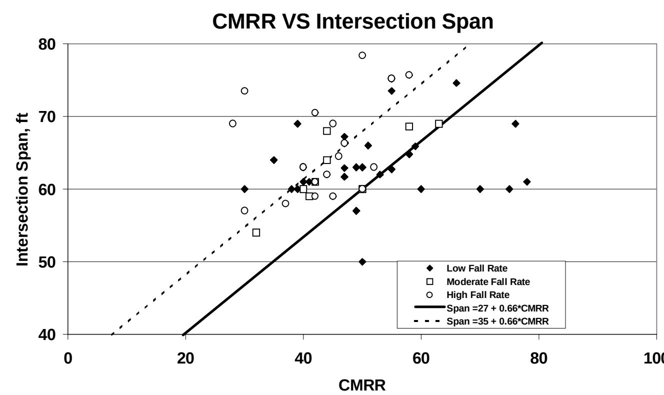

Fig. 11. Relationship between CMRR, intersection span, and roof fall rate (1 metre = 3.28 ft).

$$ALPS\ SF_R = 1.76 - 0.014\ CMRR$$

This equation can be used in design. Suggested guidelines for three different roof conditions are summarized in Table 1 (Mark, 1994).

TUNNEL DESIGN:

Wherever geologic description of the roof is important a CMRR can be calculated to lend clarity and better indicate the inherent strength of the roof. An underground haulage tunnel was being driven in an overlying coal seam to transport coal from the lower seam to a preparation plant approximately 3.2 km away (Rusnak, 1998). The life of the tunnel was expected to be 15 years. CMRR values calculated from boreholes indicated that the 0.7 m of rock above the seam was weak (CMRR 38-41), but this unit was overlain by 6 m of massive sandy shale (CMRR=75). The decision was made to take down this weak rock and bolt the roof in the massive shale. The operator considered this analysis of roof stability with the CMRR to have been successful and enhanced the value of their exploration core data.

OTHER APPLICATIONS:

Some other areas where the CMRR has been applied to ground control problems include:

1. Federal regulators (MSHA) have used the CMRR to describe the excessive strength of the immediate sandstone which contributed to a fatality in a "first fall" pillaring accident.
2. The CMRR has been used to describe the rock mass characteristics of roof for input in numerical models (Karabin, 1994).
3. The CMRR has been used to identify roof which may be at risk in the design of yielding pillars (DeMarco, 1994).
4. The CMRR has been used in the evaluation of massive pillar collapses (Chase, 1994).

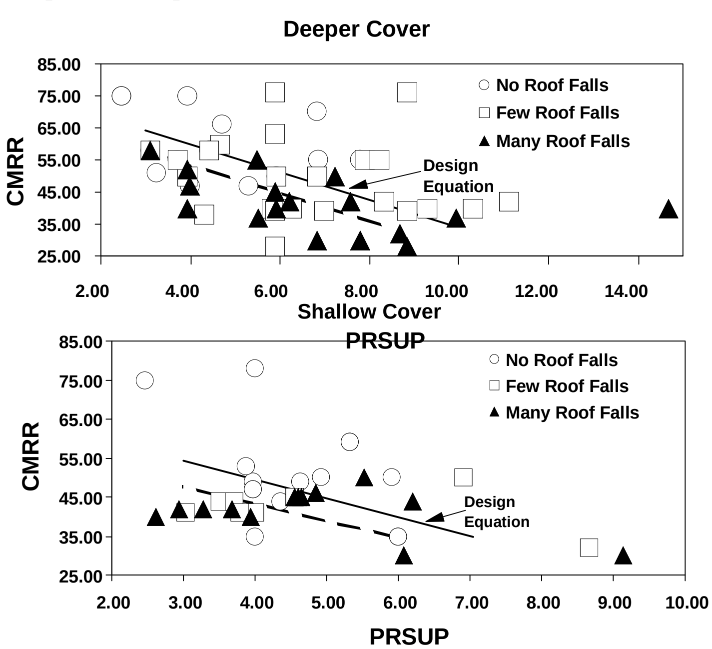

Figure 12a. Design equations for selecting bolt pattern and capacity. The field data used in the derivation of the formulas are shown along with the original "discriminate equations" (dotted line). Deeper cover (depth>120m).

TABLE 1: SUGGESTED GATE ENTRY DESIGN GUIDELINES FOR THREE TYPICAL ROOF CONDITIONS

	Weak roof (CMRR = 35)	Moderate roof (CMRR = 55)	Strong roof (CMRR = 75)
Suggested ALPS SF	1.3	1.0	0.7
Entry width, m	4.3	5.8	6.2
PRSUP	12	9	6

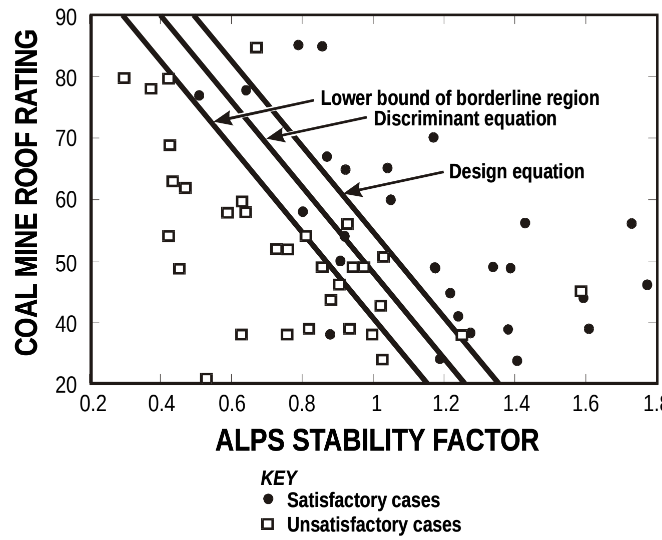

Fig. 13. Relationship between the CMRR and ALPS stability factor in U.S. tailgates.

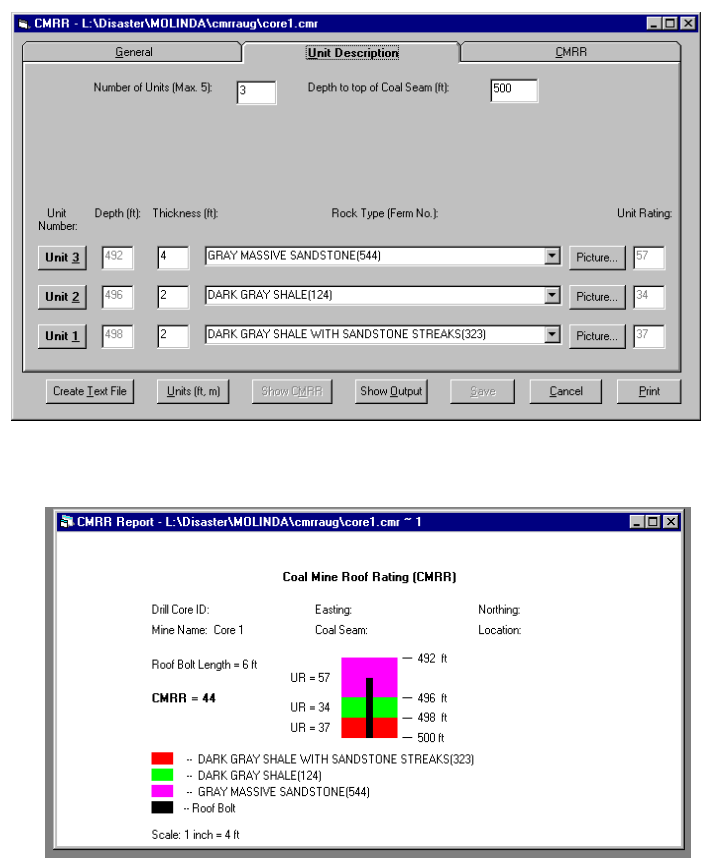

Fig. 14. Output of the CMRR visual basic program (1 metre = 3.28 ft and 1 inch = 2.54 cm).

5. The CMRR has been used in field evaluations of roof bolt performance (Signer, 1994; Mark et al, 2000)
6. The CMRR has been incorporated into guidelines for multiple seam mine design (Luo et al., 1997).
7. The CMRR has been used in hazard analysis and mapping (Wuest et al., 1996).
8. The CMRR has been used in tailgate support selection (Harwood et al., 1996).
9. The CMRR has been used in feasibility studies (Beerkircher, 1994).

CMRR computer code

The CMRR has been written to a computer code for easy application. The Visual Basic 6.0 code can be used with Windows 95, 98, and NT operating systems. It contains separate data screens for use with traditional underground exposure and also for data input from core. A complete help file also explains the CMRR philosophy and procedure as well as the individual data inputs. The output can be in ASCII text format for input to standard spreadsheet packages or graphically as a lithologic roof log with Unit Ratings and the CMRR attached. Figure 14 shows the graphical output.

Summary

The inherent strength of the coal measure rock mass is critical to the stability of mined openings. But unlike construction materials, natural rock has a continuous variability broken by structural and depositional defects. As a result, the quantitative assessment of the strength of the rock mass in the roof of coal mine openings has been difficult and descriptive at best. The CMRR has been developed to use simple field tests and observation to quantify the defects in the rock mass and translate them into an engineering value for mine opening design and support selection.

The CMRR has been used extensively to compare the strength of rock masses located in different regions and coal basins. This is necessary in property assessment, hazard mapping, and a number of economic studies including mining height and reject. By understanding even the general breakdown of CMRR values into strength, (CMRR = 0-45 weak, 45-65 moderate, >65 strong) the operator can apply a number of other analyses including support requirements, mine layout, and opening design.

Developed from observation of roof falls underground, the CMRR can now be calculated by using point load testing on core. This method provides an inexpensive alternative to extensive load frame testing. The CMRR will soon be available as an executable Visual Basic program and will be easily integrated into any standard drill exploration program.

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