Factors Influencing Intersection Stability in U.S. Coal Mines

Gregory Molinda, Research Geologist
Christopher Mark, Acting Chief, Disaster Prevention & Response Branch
Eric Bauer, Mining Engineer
Daniel Babich, Mining Engineer
Deno Pappas, Civil Engineer

National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, PA

ABSTRACT

Groundfalls are much more likely to occur in coal mine intersections than in entries. NIOSH is using the experience of U.S. coal mines to determine the factors which influence intersection instability and provide guidelines for the safe excavation and support of intersections. Detailed field investigations have resulted in a database of U.S. coal mines containing 12 mines and 639 roof falls so far. By using the roof fall rate as the outcome variable, correlations between roof geology (CMRR), intersection span, and roof support have been established. Case studies have indicated that replacing 3-way intersections with 4-way intersections may not reduce the total number of roof falls. Additionally, the size of intersection spans tend to decrease with lower (weaker) CMRR. Protocols have been established for the collections of roof bolt parameters. The performance of individual roof bolts can now be tracked with roof fall rate.

BACKGROUND

In underground coal mines, tens of thousands of intersections are driven each year. Intersections represent exposed ground which can span 25-50 ft, well over the normal width of an entry. When pillar corners are rounded to make travel easier, and when pillar spall (especially in high seams) exposes or undermines more roof, the larger spans can easily become hazardous. In 1996, there were a total of 2,824 unplanned roof falls from 892 underground coal mines. These falls resulted in 711 injuries and 8 fatalities. Of the roof falls with known locations, approximately 71% occurred in intersections. Considering that intersections account for only 20-25 % of the total drivage, on a foot by foot basis, roof falls are 8-10 times more likely to occur in an intersection than an equivalent length of entry. An estimate of number of intersections driven per year reveals the exposure hazard to miners. At a rate of 1,500 intersections driven per million tons mined and 230 million development tons in 1995, approximately 350,000 intersections are driven per year in U.S. coal mines.

INTRODUCTION

The increased likelihood of failure in intersections has been documented in the past. These studies have primarily focused on specific localized problems leading to failure, including horizontal stress and geologic discontinuities (transition zones related to paleochannels, faults) (*1,2,3*). Numerical modeling studies have confirmed that intersections are less stable than entries, and that 4-way intersections are less stable than 3-way intersections. Intersection instability was found to be dependent on rock quality and the ratio of horizontal stress to vertical stress (*4,5*). Considering that intersections are at much more risk of failure than entries, it is surprising that more attention is not given to engineering special support for intersections. Even mines with demonstrated intersection problems often do not install more support during development for these areas, preferring to rely on supplemental support when problems occur. Other secondary factors contributing to intersection failure include the quality of bolt installation (long unsupported times before bolting, oversized holes, fingergloving, etc.), and turnout frequency and location (*2,6*)).

Oversized intersection span has been identified as a cause of failure (*6,7,8*). Suggestions for controlling overspanned intersections and turnouts include longer bolts in the intersection corners near the ribline (*8*), limiting turnouts to corners not at critical angles to the principal horizontal stress direction, and sequencing crosscuts to avoid turnouts altogether.

For any given geology, there are spans which will induce entry failure. The key is defining the allowable span based on roof strength and roof reinforcement, and not to exceed it. Individual roof control plans specify maximum spans which can vary considerably between and within MSHA districts. Some roof control plans limit the sum-of-the-diagonals to 60-70 ft (Figure 1), specify the number, location, and size of turnouts in the intersection, or restrict turnouts to specific entries.

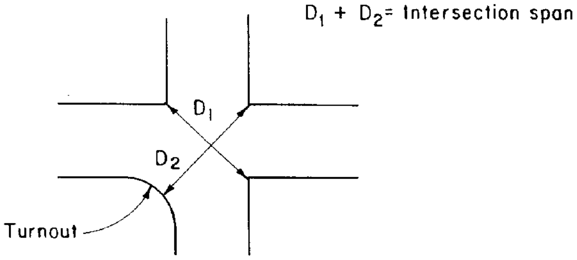

Figure 1. Sum-of-the diagonals intersection span measurement.

Rock Load and Roof Stress

Intersections may easily become overspanned if care is not taken when mining. When the roof rock is strong, small increases in span probably will not compromise the stability, but where the roof is weak, small increases in span can add significant load to the bolted interval above the intersection. If the geology is uniform, the rock-load height can be expected to be proportional to the span and to the roof rock quality, according to the equation proposed by Unal (*9*):

$$h_t = (\frac{100 - RMR}{100})\ w_e, \tag{1}$$

where h_t = Rock-load height, ft;
RMR = Rock Mass Rating, which is equivalent to the CMRR (*15*)
w_e = Entry width, ft.

This equation implies that the rock-load height above an intersection of competent roof, with an CMRR near 100, would be very small, while an intersection with incompetent roof (CMRR near 0) would have a rock-load height approximately equal to the span. Assuming that K can be substituted for the geologic adjustment factor, (100 - CMRR / 100), equation 1 can be rewritten as:

$$h_t = (K)\ w_e, \tag{2}$$

thus the rock-load height is proportional to the span.

Assuming that the rock load above the intersection can be represented as a pyramid (fig. 2), the volume of rock and rock load over the intersection can be estimated by the equation:

$$R_L = V_I\ \gamma = \frac{(w_e)\ (w_c)\ (h_t)}{3}\ \gamma, \tag{3}$$

where R_L = Rock load above intersection, lb
V_I = Volume of rock above intersection, ft^3;
γ = Unit weight of rock, pcf;
w_e = Entry width, ft; and
w_c = Crosscut width, ft.

Assuming $w_e = w_c$ in most instances, then the the rock load is proportional to the cube of the span, as shown in equation (4) where w_e and $K(w_e)$ have been substituted for w_c and h_t, respectively. If it is assumed that the rock load above an intersection can be represented by a cube (instead of a pyramid), the load is still proportional to the cube of w_e equation (5).

$$R_L = \frac{K(w_e)^3}{3}\ \gamma, \tag{4}$$

$$R_L = K\ (w_e)^3\ \gamma. \tag{5}$$

Judging from the shape of roof fall cavities, the truth usually lies somewhere in between these two idealizations. In either case, a small increase in entry width (and therefore increase in intersection span) results in a significant increase in the rock load. As figure 2 shows, increasing entry span by just two ft can increase the intersection load by nearly 40%.

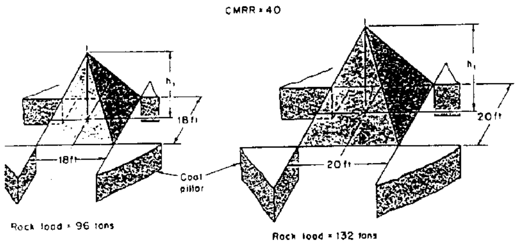

Figure 2. Comparison of rock loads above the intersection.

Where the geology is not uniform, and roof falls are truncated by an overlying self-supporting strong bed, the rock load height may be constant regardless of the intersection span. In this case, the rock load increases in proportion with the square of the span.

Roof Monitoring

Roof strain monitoring has been employed to predict imminent intersection failure. Roof monitoring and the use of early warning devices to predict intersection stability is not a widespread practice in U.S. coal mines. Roof monitoring programs have been implemented at a few mines, with generally successful results. One example was the convergence monitoring at over 600 stations in the Virginia mines of Island Creek Coal Company in the 1970's (*10*). It was found that closure rates in excess of 0.1 in/d indicate instability.

The monitoring program was thought to have prevented "numerous" falls while it was in operation (*11*). Maleki and McVey (*12*) monitored roof sag at 139 stations in 2 western U.S. coal mines. At one mine, sag rates less than 0.01 in/d denoted stability, while sag rates of 0.025 in/d was the critical sag rate that usually indicated a roof fall would occur within 8 days. At the other mine, 0.032 in/d was found to be the critical sag rate.

The use of early warning devices is a requirement in UK coal mines. Falls of ground have been dramatically reduced in British coal mines since the advent of roof bolting and monitoring in 1991 (*13*). "Action levels" of roof strain are established by roof instrumentation, and monitors are placed at maximum intervals of 65 ft (20m) of entry. Inby monitors are read every shift and recordings are made on a weekly or monthly basis. Any movement exceeding 1 in. signals the need for some remedial action, generally the installation of supplemental support. This "action level" will vary with geology and support and should be customized to each mine roof situation. These monitors cost $25-100 depending on numbers of anchors and ability to be attached to data recording systems.

NIOSH INTERSECTION FAILURE PROJECT

The NIOSH office of Mine Safety and Health at Pittsburgh Reasearch Laboratory has an ongoing project to study the factors which affect the stability of intersections. Once these factors have been identified and evaluated, the goal is to estimate the probability of failure in intersections and provide engineering guidelines for safe design and support of intersections.

The approach is to use roof stability experience of U.S. coal mines in order to determine allowable intersection spans based on geology, and to prescribe support for that span.

In order to compare the relative frequency of roof falls in coal mines, a roof fall rate was calculated for all U.S. underground coal mines using data from 1996 (*14*). Only non-injury roof falls reported to MSHA were considered in the analysis. The roof fall rate in each of the mines was calculated based on the estimated amount of entry drivage. The entry drivage was estimated from the reported production, adjusted for seam height, and whether the mine employed a longwall. The actual seam height was used in the conversion. As an example, in two mines with an equal number of roof falls and equal production, the mine with the higher seam would have a higher roof fall rate because it would have less drivage and less exposed roof. Development tons in longwall mines were estimated to be 1/4 of total annual tons. Therefore, the fall rate for longwall mines was multiplied by 4. Figure 3 shows the distribution of mines by total roof fall rate. Fifty-six percent of the mines reported no roof falls in 1996. Seventy-five percent of the mines had fall rates of .3 falls/10,000 ft of drivage or less (almost all of these mines had <10 falls in 1996). 48 mines reported 10 falls or more in 1996. While most of the mines had low fall rates, almost 50% of the falls came from mines representing only 5% of the production. This means that a large proportion of the reported falls are coming from relatively few mines. Figure 4 shows the roof fall rate (falls/ft of drivage) for intersection falls only. It mirrors the rate for all falls.

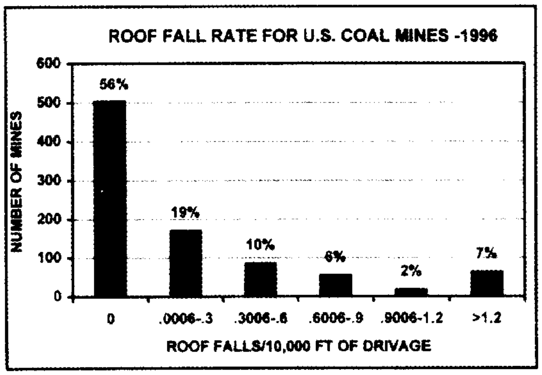

Figure 3. Roof fall rate for U.S. coal mines - 1996.

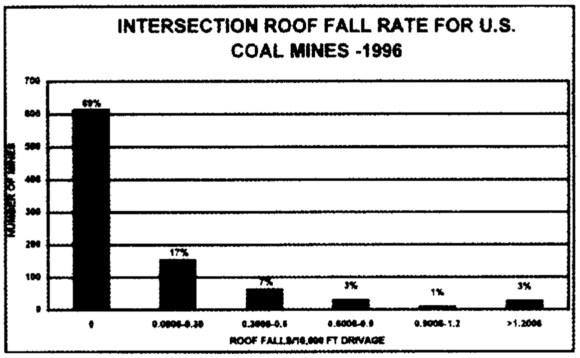

Figure 4. Intersection roof fall rate for U.S. coal mines - 1996.

Figure 5 shows the fall rate for mines by seam height. The seams with the highest fall rate are >106 in. Figure 6 shows the distribution of roof fall rates by mine size (no. of underground employees). Small mines with less than 20 employees and mines with 51-150 employees had the highest fall rates.

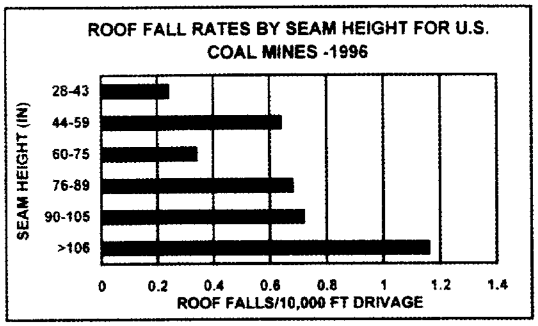

Figure 5. Roof fall rate for U.S. coal mines by seam height - 1996.

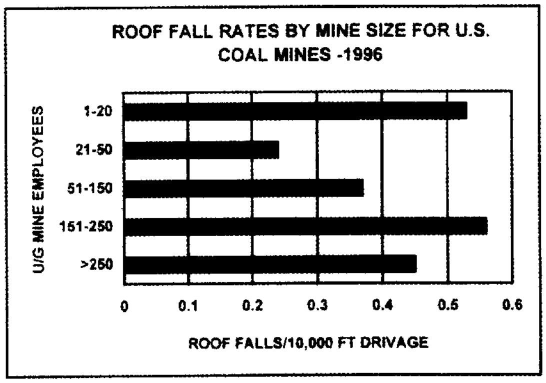

Figure 6. Roof fall rate for U.S. coal mines by mine size - 1996.

FIELD STUDY OF INTERSECTION INSTABILITY

There are a number of factors which affect the stability of coal mine roof in general and, intersections specifically. These factors include:

1. Roof geology (CMRR)
2. Entry span
3. Artificial support
4. Horizontal stress
5. Time between mining and support installation
6. Abutment

In order to study these factors, we have constructed a database of ground control variables from coal mines throughout the U.S. This database currently contains 12 mines and uses roof falls as the failure criteria. When the mine survey is complete the analysis will use a multivariate statistical approach to consider influence factors on roof falls and determine a design equation for intersection stability. Through experience the first three variables listed above have been shown to contribute most to the fall of roof. The other variables are important but are usually more site specific. In this project attention is being focused on roof geology as the key to intersection stability. In the past, empirical studies have been hampered by the large number of geologic variables which were recorded and applied to the model (e.g. uniaxial strength, RQD, thickness of the weakest bed, location of the weakest bed). Generally the influence of geology was divided between all the variables and not one of the variables exhibited a significant influence. The Coal Mine Roof Rating (CMRR) should resolve this problem (*15*).

In gathering roof stability data for each mine, standard procedures have been established to ensure data integrity. Extensive interviews with operators are conducted to identify the roof problems, establish the roof geology, and document support. From several failure criteria, the roof fall rate has been selected as the outcome variable which will be used to judge the influence of other mining and geologic variables. Non-injury roof falls are defined according to MSHA (16) as meeting any of the following criteria:

- Falls above the roof bolt anchorage.
- Falls which impair ventilation.
- Falls which impede passage of persons.
- Falls which cause miners to be withdrawn from the area affected.
- Falls which disrupt regular mining activities.

Falls of unsupported ground in the face area which do not trap equipment are normally not reported. Areas within the mine that are affected by abutment loading (longwall tailgates, pillar lines, multiple seam interaction zones) are excluded from analysis, as are zones of anomalous geology (eg. major faults). The distribution of standup time of supported ground is being determined, and data base will include only falls occurring less than 18 months after development. This is done so that roof falls that are time dependent and occur in outby areas are not given the same priority as falls near the face which expose more miners to hazard. At one mine near Providence, KY 50% of the falls occurred within one month of development, while only 10% of the falls occurred more than 12 months after development (*17*).

Roof geology is also broadly sampled by selecting mines for study which represent the full working range of CMRR. Within each mine enough roof exposures are observed to adequately define each of the significant roof types. Most often, this means visiting any and all roof falls that are accessible. CMRR verification is also done from core logs of holes on the property when possible. Roof bolts are identified on the mine map by the operator and verified underground by reading the markings on bolt heads. At the same time, immediate roof lithology is verified and intersection spans are measured. Standard procedures are followed for intersection corner location and the measurement of 3-way, turnouts, and odd intersection geometries. It is critical at intersection falls that the intersection span is measured, if possible. Eight intersections around the fall are measured to determine if any trend existed toward overspanned intersections in proximity to the fall. It is also important to measure spans in successfully supported ground in order to contrast these with failed ground.

Mine workings are then partitioned by roof bolt type and length, CMRR, intersection span, and other influencing variables like depth of cover and area beneath stream valleys. Drivages are then measured for these blocked areas in order to normalize their impact (Table 1).

TABLE 1 EXAMPLE OF DATABASE.

Mine	CMRR	Bolt Length	Tension	Grout	Bolt Capacity (Kips)	Bolts/ Row	Row Spacing	Entry Width (ft)	Intersection Span (ft)	Depth (Avg.)	Height (ft)	Roof Fall Rate*
1	45	6	yes	None	18	4	5	19	65	350	5.5	5.69
2	41	5	No	Full	18	4	5	19	59	350	5.5	1.74
3	41	6	Yes	Partial	18	4	5	19	59	350	5.5	0.29

*Roof falls per 10,000 ft of drivage

Roof fall rates (falls per 10,000 linear foot of drivage) are then calculated from the reported falls in each area. In the end, each blocked area of the mine which constitutes some combination of the above variables is assigned a roof fall rate (Fig. 7). In this way the contribution of each variable to the roof fall rate can be calculated and converted into the regression equation.

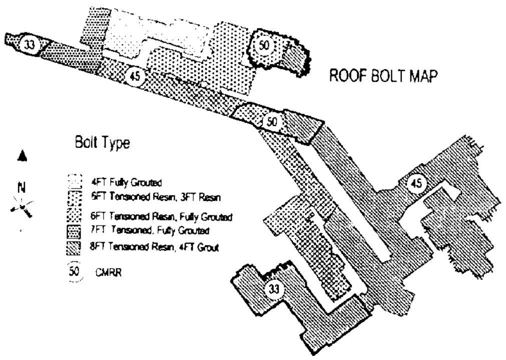

Figure 7. Example of partitioning of mine with overlapping geologic and bolt variables.

Current Database Results

The following are summary data from the current database. From 12 mines, over their entire existence, a total of 639 roof falls were tabulated. Roof fall rates were calculated per 10,000 ft of drivage for each mine (Fig. 8). The fall rate for intersections was also calculated. The mines are located in most of the major coal basins in the country and include small mines, large mines, room and pillar operations, and longwalls. The final data set will contain about 30 mines and will cover a range of poor roof to strong roof.

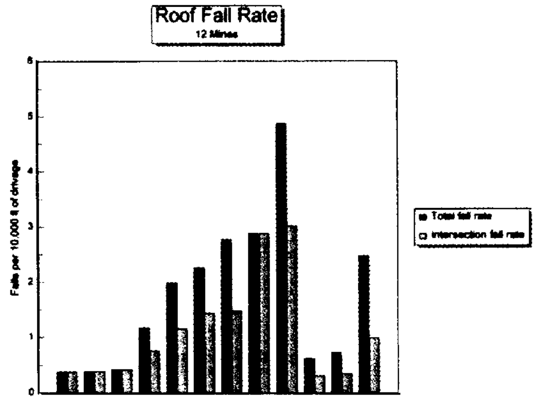

Figure 8. Total and Intersection fall rates for each of the mines in the database.

The roof falls which make up our mine sampling are classified by location in intersections or entry segment (the mined entry between intersections). Of the falls now included in the database, 59% now occur in intersections.

In order to compare the stability of intersections vs. entry segments, the falls were calculated as a percentage of total mined places fallen. Figure 9 shows that intersections were 2.5 times as likely to fall as entries. Individually in the 12 mines, the ratio of failed intersections to failed entries ranged from 1.5 to 3.3.

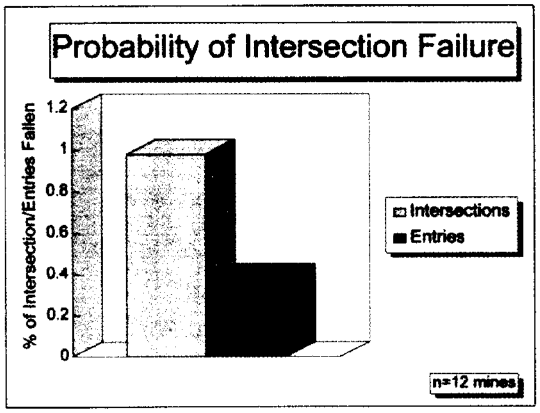

Figure 9. Comparison of intersection and entry failure rates.

The relative stability of the type of intersection (3-way vs. 4-way) was also investigated using the preliminary data from the 12 mine database. The percentage of 3-way and 4-way intersections was tabulated. Then the percentage of 3-way falls and 4-way falls was determined. Figure 10 shows the proportion of 3-way vs. 4-way falls in comparison to the percentage of all of these types of intersections. 42% of all intersections were 3-ways, but only 36% of all falls in intersections were in 3-ways. 58% of all intersections were 4-ways, but 64% of all falls in intersections were in 4-ways. Proportionately there was a higher fall rate in 4-ways than 3-ways. In this data set then, a 4-way intersection is 1.28 times as likely as a 3-way to fall. However, since it would normally take two 3-way intersections to replace one 4-way, the remedy of replacing 4-ways with 3- ways is not likely to reduce the number of roof falls. It would take a fall rate of at least twice as high for 4-ways to consider replacing them with 3-ways. A mine that systematically replaced 4-ways with 3-ways would be expected to see a 56% increase in total number of falls.

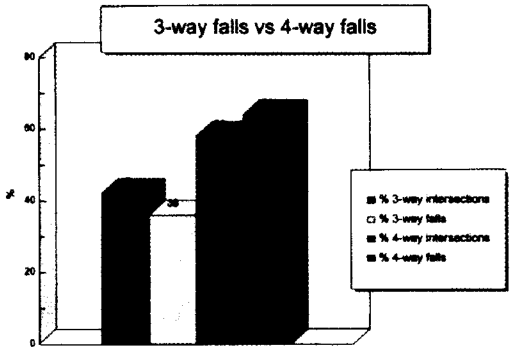

Figure 10. Failure rate of 3-way vs. 4-way intersections.

Coal Mine Roof Rating

Past experience at individual mines demonstrates a correlation between CMRR and roof fall rate. (11). Roof fall rate decreased as the CMRR increased. The CMRR for the database ranges from 32 (extremely weak) to 75 (very competent). Figure 11 shows significant variation in fall rate with individual CMRR, indicating that other factors also influence the fall rate. Individual mines show variable degrees of correlation between CMRR and roof fall rate. At one mine in Mingo Co., WV the roof fall rate for a weak shale (CMRR = 40) was 3.4 per 10,000 ft of drivage, while the roof fall rate for a firm shale or stackrock (CMRR = 50) was 1.0 per 10,000 ft of drivage. Both rock types were bolted with 48 in fully grouted bolts.

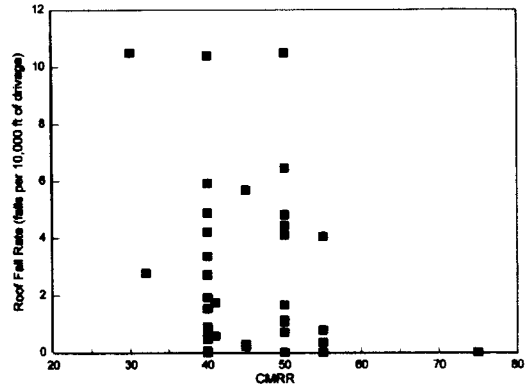

Figure 11. Relationship of CMRR to roof fall rate.

A relationship was found between CMRR and intersection span (Fig. 12). Generally, as CMRR increased in the 12 mines in the database, the average intersection span (sum-of-the-diagonals) increases. Factors such as roof support and local mining practice influence this relationship. This may indicate that operators know from experience that stronger roof is better able to support a larger span and this is reflected in their mining widths.

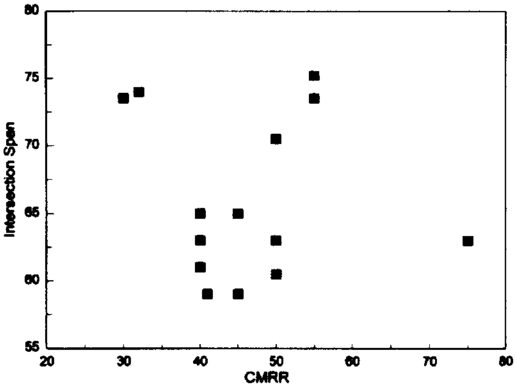

Figure 12. Relationship of CMRR to intersection span.

Intersection Span

The average intersection spans were calculated for each combination of variables comprising each mine partition and represented as one row in the database. Figure 13 shows the correlation between intersection span and roof fall rate for all CMRR values of 45 and below. One mine with a wide intersection span (74 ft) and a lower roof fall rate (2.78) can be explained because heavy steel sets may be supporting failed roof and contributing to a lower roof fall rate. The CMRR values represent the weakest roof. The weakest roof rocks are the most sensitive to large spans and have the highest roof fall rates.

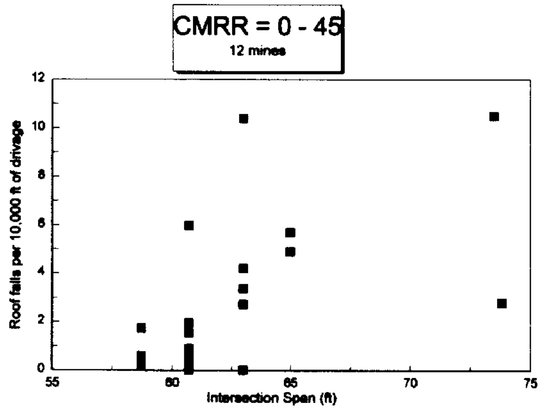

Figure 13. Relationship of intersection span to roof fall rate for weak rocks.

A number of ways to minimize intersection spans have been proposed. In one Pennsylvania mine, roof conditions deteriorated in wide intersection spans (one diagonal measured 52 ft) when a track chute entered a panel and also intersected a crosscut. By dropping one crosscut and staggering another, the span was reduced. Reducing the number and location of turnouts should result in reduced intersection spans. The practice of driving crosscuts straight across the developed entries, where possible, as well as supporting at-risk intersections before they become intersections, will stabilize spans (8).

Roof Bolting

There were numerous bolt types, lengths and spacings used in the twelve mines. These ranged from 4 ft to 12 ft lengths, tensioned and untensioned bolts, and ungrouted, partially grouted, and full-column grout. Bolt spacing varied from 3-5 bolts per row and 4-6 ft row spacing.

Poor roof bolt installation may be able to account for some of the variation in the roof fall rate regression model. This topic includes the following: long lag times before bolting, overdrilled holes, loss of tension, loss of resin due to lack of containment, etc. This type of data can be important but very difficult to obtain. In one mine we found a high rate of tension bleed off (55% of bolts tested had lost tension). Also a significant number of bolts observed in roof falls were "finger-gloved," indicating the resin was not mixed properly. Long bolting lag times are more damaging in laminated rock with a CMRR in the 40's or below. Data shows that 50-80% of the total deformation and load changes occur within a few hours or days after initial excavation (*8*).

Case History

At one western Pennsylvania mine in the Pittsburgh seam 55 intersection diagonals were measured. The measured data considers intersection spans in fallen areas and non-fallen areas. The falls observed in this mine were cleaned up and accessible. The most significant observation was that for 83% of the roof falls, the sum-of-the-diagonals exceeded 70 ft (Fig. 14). In contrast, none of the non-fallen bolted intersections had a span exceeding 70 ft. As the span increases so does the amount of support. Supplemental support was necessary in 10 intersections where the average span was 67.1 ft. Although none of these were fallen, they required additional support to stabilize them. The mean span for the roof falls at this mine is only 11% greater than the mean for the stable intersections, but the estimated rock load is 43% greater. The CMRR for this mine is 40, typical of the Pittsburgh seam. The correlation of increased span with more roof falls is an indication that a sum-of-the-diagonals of 70 ft or less is necessary for stable roof in this geology.

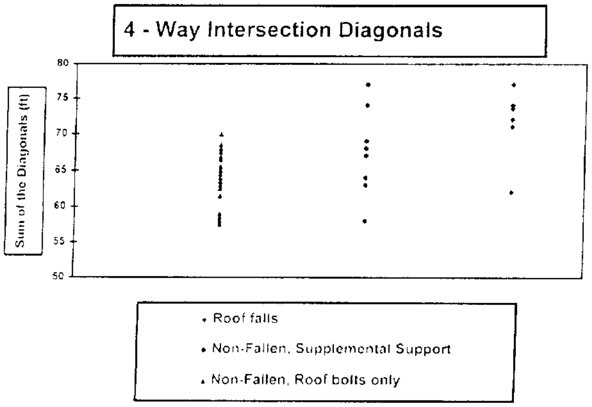

Figure 14. Intersection spans for roof bolts, supplemental support, and fallen roof areas at an eastern coal mine.

Mining method has also played a role in intersection stability at this mine. Where a miner-bolter was used to drive development sections there was a dramatic improvement in roof conditions. No falls have occurred in development by miner-bolter. If the roof fall rate in these areas were the same as that of areas driven by place-change miners, 10 falls would have been expected. The improvement may have been due to the smaller entry width and intersection span resulting from the miner-bolter, or to quicker roof support installation, or a combination of both.

CONCLUSIONS

By using the roof stability experience of the U.S. coal mining industry, a model of the parameters which influence roof failure is being developed. Through a system of monitoring standup time of roof falls, and sorting out anomalous causes of falls (abutment loading, unusual geology, etc.), roof falls are counted and roof fall rates are assigned to partitioned areas of the mine. Then roof geology is determined, intersection spans are measured, and roof bolts are documented for each partition.

MSHA and NIOSH roof fall data has shown that intersections are, on a foot by foot basis, about 8-10 times more likely to fall than entries. Three variables appear to have the most influence on roof fall rates:

- Coal Mine Roof Rating - For the weakest group of roof rocks (CMRR<= 45), roof fall rates increase for increasing sum-of-the-diagonals intersection span, indicating that weak rocks have some limit of stable span. Variability in this correlation is due to increased support in at-risk intersections. It is critical to accurately define the roof fall rates for CMRR in the weakest roof rocks in order to anticipate instability.

- Intersection Span - For the entire range of CMRR in the sample population, intersection span increases with increasing CMRR, confirming that stronger rocks can support bigger spans. It is the transition zones between weak, moderate, and strong CMRR ranges which have to be better defined. Case studies have indicated that replacing 3-way intersections with 4-way intersections may not reduce the total number of roof falls.

- Roof Support - Individual case histories show various roof fall rates attached to different support. At one mine supplemental support was necessary in numerous intersections where the span exceeded 67 ft. At another mine loss of bolt tension in 55% of the tested bolts may have contributed to the extremely high roof fall rate. At another mine, roof falls were dramatically reduced by the use of 8 ft point anchored, resin-assisted bolts. These types of individual results will be more meaningful when analyzed relative to the whole database.

The effects of mining method (miner-bolter vs place change mining and practice (intersection development, poor roof bolt installation) also have an impact on intersection stability. When complete, the database will contain data sets on 30-35 U.S. coal mines and a multivariate analysis will be used to determine the influence of each variable on the ultimate stability of an intersection.

FUTURE RESEARCH

We will continue to collect field data from coal mines and expand our data base to include 30-35 mines. With that data as input, a multivariate analysis will be applied. The end goal will be to develop a design model for the safe excavation and support of intersections.

REFERENCES

1. Blevins, C.T., and Dopp, D. Ground Control Experiences in a High Horizontal Stress Field at Inland Steel Coal Mine No. 2. Paper in Proceedings of the Fourth Conference on Ground Control in Mining, Morgantown, WV, July 22-24, 1985, pp. 227-233.
2. Hanna, K. and Conover, D. Design of Coal Mine Entry Intersections. Soc. Min. Eng. AIME Preprint No. 88-39, 1988, 11 pp.
3. Ingram, D.K. and Chase, F.E. Effects of Ancient Stream Channel Deposits on Mine Roof Stability: A Case Study. U.S.B.M. RI 9092, 1987, 33pp.
4. Gercek, H. Stability of Intersections in Room and Pillar Coal Mining. Ph.D. Thesis, Pennsylvania State Univ., 1982, 186 pp.
5. Unal, E. Development of Design Guidelines and Roof Control Standards for Coal Mine Roofs. Ph.D. Thesis, Penn State, 1983, 355 pp.
6. Peng, SS. Roof Falls in Underground Coal Mines. Dept. of Mining Engineering, WVU, Morgantown, WV, Technical Report No. TR 80-4, September, 1980, 44 pp.
7. Mark, C., Molinda, GM., Schissler, AP., and Wuest, WJ. Evaluating Roof Control in Underground Coal Mines With the Coal Mine Roof Rating. Proceedings of the 13th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV, August 2-4, 1994, pp. 252-260.
8. Hanna, K. and D.P. Conover. Design of Coal Mine Entry Intersections. Paper at SME Annual Meeting, Phoenix, AZ, Jan. 25-28, 1988.

9. Unal, E . Empirical Approach to Calculate Rock Loads in Coal Mine Roadways. Proceedings Fifth Conf. On Ground Control in Mining, West Virginia University, Morgantown, WV, June 11-13, 1986, pp. 234-241.

10. Pothini, B.R. and H. von Schonfeldt. Roof Fall Prediction at the Island Creek Coal Co. Proceedings of the 1st International Symposium on Stability in Coal Mining, Vancouver, 1978, pp. 215-227.

11. Mark, C., Watts, R., Marshall, T.E., and M.O. Serbousek. Using Computerized Mine-Wide Monitoring for Ground Control. Proceedings of the SME Annual Meeting, Albuquerque, New Mexico, February 14-17, 1994.

12. Maleki, H.N. and J.R. McVey. Detection of Roof Instability by Monitoring the Rate of Roof Movement, BuMines RI 9170, 1988, 12pp.

13. Altounyan, PFR., Bigby, DN., Hurt, KG., and Peake, HV. Instrumentation and Procedures for Routine Monitoring of Reinforced Mine Roadways to Prevent Falls of Ground. Paper in Proceedings of the 27th International Conference of Safety in Mines Research Institutes, New Delhi, India, 1997, pp. 759-766.

14. MSHA Accident Employment Database (1996).

15. Molinda, G.M. and Mark, C. Coal Mine Roof Rating (CMRR): A Practical Rock Mass Classification for Coal Mines. U.S.B.M. Information Circular 9387, 1994, 83 pp.

16. CFR 30, Part 75.223, 1989, pg. 502.

17. Available from G. Molinda