

## GROUND CONDITION MAPPING: A CASE STUDY

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### ABSTRACT

The Mine Safety and Health Administration (MSHA) issued Program Information Bulletin P09-03 in April of 2008, providing formal guidance on using programs that model the redistribution of stress during underground mining of coal. A key part of this guidance is visual observation and mapping of ground conditions. If a correlation between ground conditions and model output can be established, the model is considered to be verified, and can be used to guide mine design in similar ground. A simple scale is recommended for ranking observed roof, rib, and floor conditions. This paper discusses optimization and implementation of a ground condition rating scheme in the gateroads of a deep underground longwall coal mine. Roughly 80% of each gateroad length deteriorated in a fairly uniform manner. However, this manner varied between gateroads, as did pillar size. The implementation of a ground condition mapping program, similar to that recommended in PIB 09-03, was successful in characterizing the ground response to mining in gateroads of a longwall coal mine.

### INTRODUCTION

The growing use of modeling, in both design and accident investigation, was recently evident in the Crandall Canyon investigation report (Gates et al., 2008). In the wake of this investigation, the Mine Safety and Health Administration (MSHA) issued Program Information Bulletin 09-03 (Skiles and Stricklin, 2009), providing guidance on the use of programs to model the redistribution of stress during underground mining of coal. Systematic observation of ground deterioration is a key part of this guidance to support development and verification of a stress model of the district. However, published guidance and experience for implementing an observational program was found to be rare. The NIOSH Office of Mine Safety and Health Research (OMSHR) sought to address this by conducting a case study in a longwall coal mine. Ground deterioration was rated during mining of the first panel of a new district. This paper describes adaptation of the ground deterioration rating system to this site, the experience gained in its implementation, and some typical results.

### Case Study Site

This case study was developed in the gateroads of a deep western longwall operation during mining of the first panel of a new district (figure 1). These three-entry gateroads are identified as the 1 and 2 North gateroads. Pillars in 1 North, located adjacent to the district barrier pillar, were significantly smaller than in 2 North (figure 1). Overburden in the study area ranges from 450 to 700 meters (1,500 to 2,300 feet).

Observations were intensified in areas near borehole pressure cells installed to measure pillar loading at two locations in each of the gateroads, in an attempt to correlate observations with pressure cell data. While discussion of pressure cell data is beyond the scope of this paper, the placement of the instrumentation helped to define the mapped study sites.

The 1 and 2 North gateroads are intersected at a low angle by several regional faults. Normal offset on the faults is on the scale of 0.3 to 3 meters (1 to 10 feet). In some cases, faulting has had an observable adverse effect on ground control shortly after and during development, and has been associated with more pronounced

deterioration after influence from the longwall. Other mines in the area report having similar challenges related to regional faulting.

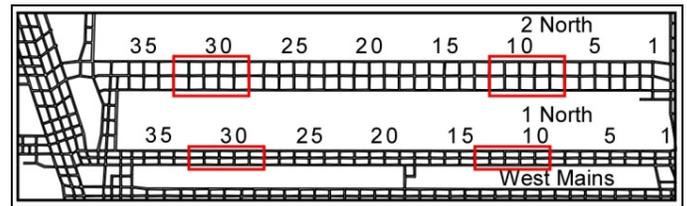


Figure 1. Mine map showing two gateroads of a new district. Survey areas near instrumented sites are highlighted. Crosscut numbers are labeled at every fifth break.

### PIB 09-03 Guidance

MSHA released "General Guidelines for the Use of Numerical Modeling to Evaluate Ground Control Aspects of Proposed Coal Mining Plans" as PIB 09-03 (Skiles and Stricklin, 2009). This document attributes development of the method to MSHA, Technical Support, Roof Control Division, and references the work of Karabin and Evanto (1994), who applied boundary element models to the design of underground coal mines as a basis.

These guidelines break the model verification and application process into eight steps, as follows:

1. Observe Underground Areas
2. Estimate Model Parameters
3. Model Observed Areas
4. Verify Model Accuracy
5. Establish Threshold Limits
6. Model New Configurations
7. Evaluate New Configurations
8. Implement Best Alternative

A key requirement is step 4 – verify model accuracy – which is described as the "the most critical step." In this case, "verification" refers to establishing that observed ground conditions correlate with model output. A verified model can be used to anticipate how conditions might respond to changes in depth, gateroad pillar size, panel dimensions, barrier pillar dimensions, district geometry, etc. Thus, numerical modeling cannot be conducted in accord with this guidance without observation and rating of ground conditions.

### Deterioration Index Review

The PIB recommends assigning a "numerical rating on a scale 0-5 . . . in each of the three categories: pillar, roof and floor," and specifies the method as published by Karabin and Evanto (1994), listed in tables 1 through 3. Karabin and Evanto synchronized their indices at two points, with a score of 2.5 indicating "stability concerns" and 3.5 indicating "corrective action is required."

Heasley and Chekan (1998) applied this approach in a manner largely consistent with Karabin and Evanto (1994). However, their implementation (table 4), introduced three significant variations. First, they chose to focus solely on rib conditions. Second, they eliminated references to "stability concerns" and "corrective action is required." Third, they supplemented qualitative descriptors such as "slight" and

“severe” with more quantitative measures of the amount of coal that has broken from the rib.

**Table 1.** Pillar deterioration indices as defined by Karabin and Evanto (1994).

<b>PILLAR DETERIORATION INDEX</b>	
<b>0</b>	Virtually no sloughing
<b>1.0</b>	Corner sloughing
<b>2.0</b>	Light perimeter sloughing
<b>2.5</b>	Onset of pillar stability concerns
<b>3.0</b>	Significant perimeter sloughing
<b>3.5</b>	Supplemental support required
<b>4.0</b>	Severe perimeter sloughing
<b>5.0</b>	Complete pillar failure

**Table 2.** Roof deterioration indices as defined by Karabin and Evanto (1994)

<b>ROOF DETERIORATION INDEX</b>	
<b>0</b>	Virtually no deterioration
<b>1.0</b>	Flaking or spalling
<b>2.0</b>	Cutter roof
<b>2.5</b>	Onset of roof stability concerns
<b>3.0</b>	Broken roof
<b>3.5</b>	Supplemental support required
<b>4.0</b>	Significant roof falls
<b>5.0</b>	Widespread and massive roof falls

**Table 3.** Floor deterioration indices as defined by Karabin and Evanto (1994)

<b>FLOOR DETERIORATION</b>	
<b>0</b>	Virtually no deterioration
<b>1.0</b>	Sporadic cracks
<b>2.0</b>	Consistent localized cracks
<b>2.5</b>	Onset of floor stability concerns
<b>3.0</b>	Widespread cracks and obvious heave
<b>3.5</b>	Travel impact-grading required
<b>4.0</b>	Significant floor displacement
<b>5.0</b>	Complete entry closure

**Table 4.** Rib deterioration index used by Heasley and Chekan (1998).

<b>RIB DETERIORATION</b>	
<b>0</b>	Rib still intact with no sloughed coal, original rock dust still in place.
<b>1</b>	Very slight pillar sloughage, some broken coal at base of rib.
<b>2</b>	Slight pillar sloughage, broken coal covers one third of rib.
<b>3</b>	Significant pillar sloughage, broken coal piled halfway up rib.
<b>4</b>	Severe pillar sloughage, broken coal piled almost to roof.
<b>5</b>	Rib is composed of completely broken coal at the angle of repose, pillar may be failed.

### RATING SYSTEM DESIGN

In setting out to design a rating system for this particular site, a number of factors were deemed essential to success. These include:

- Ratings should satisfy the functional requirements, if not the form, set out in the MSHA PIB. That is, they need to quantify the character and progress of ground deterioration that is relevant to ground control safety. By doing so, they provide a foundation for validating ground stress models that can anticipate the consequences of design decisions in future mining areas.
- Ratings have to be clear and consistent – in both development and later interpretation. That is, subjective interpretation by both raters and users should be minimized so that there is a clear and consistent understanding of the conditions at a rated location. The addition of quantitative standards, wherever possible, should be undertaken.
- Ratings need to be relatively simple, so as to be easily learned and applied by both raters and users. To this end, it

is useful to “tune” rating criteria to the failure modes that are both active at and important to the study site.

- The rating scheme should be flexible. The scheme must be reviewed periodically to evaluate whether modifications are needed to incorporate new modes of deterioration. This is a particular concern where local geologic conditions may drive significantly different or more intense deterioration. Conditions outside the expected range should be carefully noted.
- Finally, the safety, time expenditure, and training requirements of those conducting the surveys should be taken into consideration.

Like Heasley and Chekan, we attempted to adapt the rating system of Karabin and Evanto (1994) to our particular site and project. In doing so, an attempt was also made to expand and quantify the description of conditions at each level to minimize subjectivity, and to assure consistency of results between observers. This was particularly important to this research effort because our staff were not based on-site, but rather made periodic visits to monitor conditions and perform other research duties.

The quantification introduced by Heasley and Chekan has been expanded to include roof and floor. It has also been expanded to reflect specific conditions and failure modes at the study site. In addition, quantitative measures were added wherever possible.

The reason for this quantification is that observations are inherently subjective, and ratings were initially found to vary between observers. By explicitly describing those conditions that merit a specific numerical rank, the discrepancies between ratings collected by different observers were limited. Ideally, ratings by multiple observers with minimal task training will have few, if any, inconsistencies.

It is also necessary to account for differing backgrounds of individual observers. Ideally, the system can be implemented by geologists, engineers, and production staff with varying amounts of experience. By describing, in detail, conditions of concern, the influence of a specific observer’s background is reduced. Where we have fallen short of this ideal, occasional cooperative mapping has proven to synchronize ratings.

The criteria defined in deterioration indices for a mine should be specific to that mine, although there are likely to be commonalities with other mines as well, and result from a compilation of in-mine observations. Correlation of modeling output with specific index ratings requires that the criteria conditions have been observed at that location and are associated with increased deterioration. For example, cutter roof may be indicative of deteriorating conditions at one mine, but it would be inappropriate to include the presence of cutter roof as an index rating criteria for a mine where no cutters occur. In other words, a similar but different rating system will likely be needed in different geologic settings.

We also follow the lead of Heasley and Chekan in eliminating references to “stability concerns” and “corrective action is required.” While such judgments are important, and may draw heavily on observation of ground conditions, they may involve additional factors and require expertise beyond that needed for basic deterioration mapping. For example, evaluation of stability may require reference to previous experience, analysis, and possibly testing in addition to observation. Similarly, the need for corrective action depends on many factors, including the entry’s function. Thus, while ratings may inform these decisions, the decision itself might be best left as a product, rather than an integral part of, the rating system. Moreover, as investigators, it was not appropriate to insert ourselves into operational and safety decisions made by the mine and MSHA. Entries mapped during our investigation were rehabilitated and received supplemental support as needed. These decisions were made independently of our observations. One interesting result of these efforts was that they, on occasion, reduced the level of apparent deterioration. This possibility needs to be considered in attempting to validate a model against observed deterioration as specified in the MSHA PIB.

The resulting rating system is presented in Tables 5 through 7. Entry surveys were conducted by observers walking the entry length, taking care to observe conditions in the ribs, roof, and floor. An average rating is recorded for an interval spanning between crosscuts. For instance, beginning at crosscut 1, an observer may walk down entry 2, ending the first interval at crosscut 2. Suppose that the ribs on average appear to have shed approximately 0.3 meters (1 foot) of coal but remain otherwise intact—the floor has not visibly heaved, and the roof does not sag, but joint apertures are open by 1.3 cm (½ inch) and a large slick runs subparallel to the entry for a distance of 15 meters (50 feet). These conditions would result in a rib rating of 1, a floor rating of 0, and a roof rating of 1. Since ratings are an average over this interval, they do not necessarily reflect the worst condition encountered. The floor heave rating roughly correlates with the number of feet that the floor has been uplifted. However, with averaging, sporadic 0.6 meters (2 feet) of uplift of the floor may be rated 1 or 1.5. A rating of 2 would require consistent heave in the interval between crosscuts. Subsequent grading of the floor may reduce the level of apparent heave, and thus lower the rating. It should also be noted that the results of surveys conducted during the course of this study were intended for correlation with numerical models, not hazard mapping. In the event of hazard mapping, averaging ratings is not recommended.

Two types of rib deterioration were found to be suitable for rating. These are “sloughed” – creation of large onion-skin-like sheets of coal and “rubblized” – coal broken into small pieces. In addition, the rib-roof interface was inspected for detachment, i.e. formation of a gap.

Ribs were consistently bolted and meshed. Sloughed layers were contained by the screen, preventing the accumulation of large slough piles at the base of ribs. Rubblized coal material was often small enough to slip through screen and accumulate. However, rubble was also regularly removed from entries. Removal of rubblized coal from the entry floor may change the apparent rating, and should be noted. For these reasons, estimated depth of coal loss into the pillar is a more reliable indicator of rib deterioration than accumulation of a slough pile at this mine. Different rib control and entry maintenance practices at other mines may result in different rating criteria.

**Table 5.** Rib rating criteria.

<b>RIB RATING CRITERIA</b>	
<b>0</b>	No sloughing.
<b>1</b>	Ribs show minor sloughing, with sloughing extending an average of less than 0.5 meters (1.5 feet) into the rib. Sloughing appears to be limited to the pillar skin. Large dislodged blocks are not observed or are infrequent. Rubblized zones are not observed. Rib/roof contacts are largely intact, although minor separation may occur.
<b>2</b>	Ribs show moderate sloughing, extending an average of less than 1 meter (3 feet) into the ribs. Blocks of coal may begin to separate from the rib, but are not rubblized and remain in place. These blocks may be slightly rotated, disturbing apparent cleat orientation. The roof/rib interface is often separated on at least one side.
<b>3</b>	Ribs show slightly more severe sloughing. Sloughing has extended into the rib for as much as 1.5 meters (5 feet), but generally less. Limited intervals of rubblized rib may be observed. Zones where significant amounts of coal have been shed from the ribs are generally less than 4.5 meters (15 feet) wide. The roof/rib interface is often separated on at least one side.
<b>4</b>	Ribs show severe sloughing. Intervals of rubblized rib are extensive, and rubble locally spills out of rib mesh. Walkways are narrowed by accumulation of shed rib material. Depth of sloughing locally exceeds 1.5 meters (5 feet). Mesh and/or rib bolts may be damaged by sloughing rib material. Rib/roof interfaces have separated.
<b>5</b>	Ribs show severe sloughing. Accumulated rib material at the can line is significant, 0.5 meters (1.5 feet) deep or more. Travel may be unsafe.

Roof rating focuses on roof discontinuities at lower ratings. Creation of new tension fractures and opening of all discontinuities are

tracked. Ratings for slickensided discontinuities are increased by one, as they are inherently weaker in shear. Higher ratings also consider the degree of roof and roof support failure.

**Table 6.** Roof rating criteria.

<b>ROOF RATING CRITERIA</b>	
<b>0</b>	The roof shows no signs of deterioration. There is no sagging, tension cracking, deformation of roof bolts and mesh, or visible yield in standing support. Joint apertures are tight and there are no exposed slicks in the roof.
<b>1</b>	Tension cracks begin to form, most are parallel or sub-parallel to entries. Existing joints and newly formed tension cracks open slightly, with apertures smaller than 1.3 cm (½ inch). Open joint apertures are much more common than tension cracks. Tight slickensided discontinuities also justify this rating. These often occur as concentrations of radial and/or linear slicks, pre-bolting falls, and other local geological features. The roof does not sag and there is no observable yield on roof support.
<b>2</b>	Tension cracks extend and are more common. Discontinuity apertures open to an average of 1.3 cm to 2.5 cm (½ inch to 1 inch). Local distortion of roof support may be evident.
<b>3</b>	Tension cracks and joint apertures open to an average of 2.5 cm (1 inch) or greater. The roof is beginning to sag locally. Tension cracks are pervasive. Minor, local loss of roof material is apparent in the roof mesh. Bolt anchorage, however, is unaffected. Roof support may be yielding.
<b>4</b>	The mesh is visibly bagged with roof rock. Roof failure locally extends to and above the bolting horizon. Mesh and other support materials are locally damaged by dislodged roof rock. Roof support is yielding. Roof conditions are locally hazardous.
<b>5</b>	Roof failure is extensive, not merely local. Bolt anchorage and mesh are at least locally compromised, and have fallen along with broken roof rock. Roof conditions are hazardous through most of the entry.

**Table 7.** Floor rating criteria.

<b>FLOOR RATING CRITERIA</b>	
<b>0</b>	There is no visible floor heave, and the floor does not produce a hollow sound.
<b>1</b>	The floor may show no visible heave, but may produce a hollow sound or there may be very limited heave. Floor heave may not be continuous throughout the entry and is uplifted by generally 0.3 meters (1 foot) or less.
<b>2</b>	There is some limited floor heave. Floor heave is generally less than 0.8 meters (2.5 feet) uplifted, and may or may not be continuous.
<b>3</b>	Floor heave is more or less continuous throughout the observed area and is uplifted by an average of 1 meter (3 feet).
<b>4</b>	Floor heave is continuous throughout the observed area and is uplifted by greater than 0.6 meters (2 feet) but less than 1.4 meters (4.5 feet).
<b>5</b>	Floor heave is continuous and uplifted by greater than 1.4 meters (4.5 feet).

The photograph in figure 2 is an example of “rating 3” roof deterioration. Although no tension cracks are visible in the photograph, the roof is clearly sagging. Rubblized roof material is contained in the mesh, causing it to bulge outward.

The photograph in figure 3 is an example of “rating 1” rib deterioration. The rib is sloughing less than 0.5 meters (1.5 feet) of material, which is effectively contained in the rib mesh. The dislodged material has detached in large slabs and has not rubblized.

The photograph in figure 4 is an example of “rating 4” floor deterioration. Floor heave in the photograph is approximately 1 meter (3 feet) uplifted, and is continuous.

## RESULTS

Gate road observations were characterized through three phases of mining development, longwall approach, and side gob development.



Figure 2. A photograph demonstrating level 3 roof deterioration.



Figure 3. A photograph demonstrating level 1.5 rib deterioration.

Gateroad conditions began changing as the longwall approached, as can be clearly seen in plots of deterioration against distance to the longwall face. Such plots can be easily compared to model results. A plot typical of the middle entry assessment in gateroad 1 is presented in figure 5. The effect of longwall loading is evident about 300 meters (1000 ft) outby as first roof, and then rib, deteriorate. The floor remains intact. This pattern was found to be typical of about 80 percent of the entries in gateroad 1. Ground response begins to vary by entry as the longwall passes, and the side gob becomes increasingly important.

Notes on the mechanism of roof deterioration were taken during entry surveys as well. A consistent pattern of roof deterioration was observed in the middle entry with approach and passage of the longwall face. Roof sag became pronounced with face advance, developing from isolated to continuous. Sag was accompanied by further opening of roof joints and creation of deep tension cracks oriented parallel to the gateroad to sub-perpendicular to jointing.

Rubblization of the roof was focused between the two center-most roof bolts, creating an obvious bulge in the mesh. This bulge eventually split, spilling rubble onto the floor. Mesh bagging and failure were consistent rather than local, appearing as a "zipper-like" failure along the length of the entry. Roof straps were kinked at their centers as if they had been laterally compressed. Further caving and rib degradation closed the entry entirely, typically within 60 meters (200 feet) inby of the face-line.



Figure 4. A photograph demonstrating level 4 floor heave.

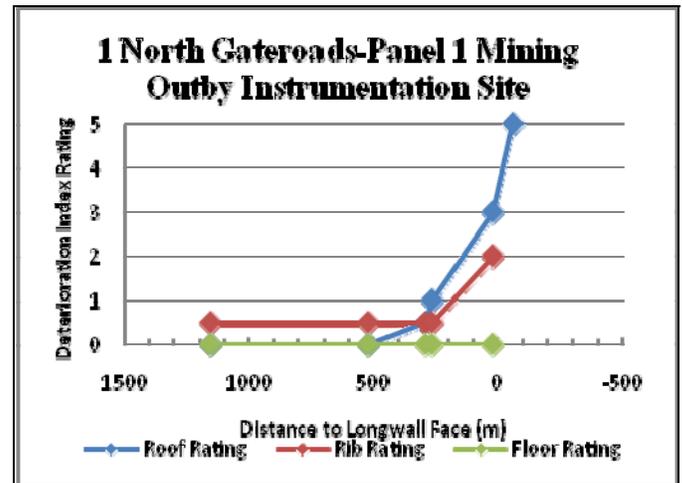
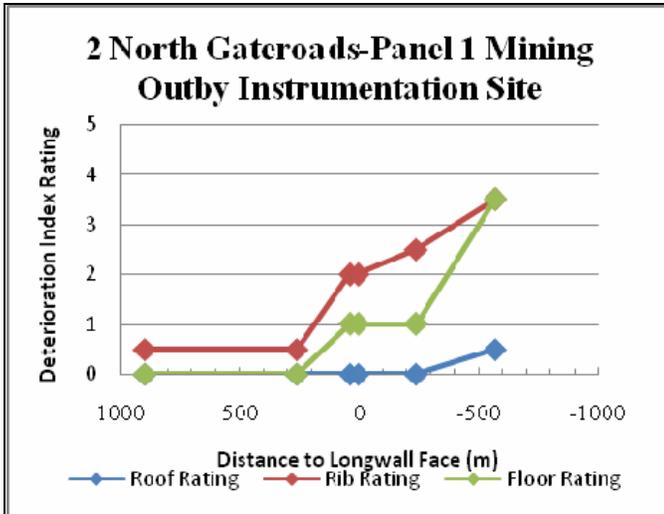


Figure 5. Deterioration ratings in the middle entry at the midpoint between crosscuts 9 and 10 in 1 North, an instrumented location, relative to the longwall face position.

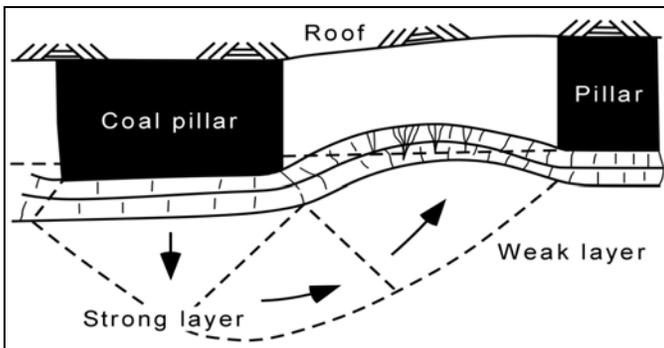
The remaining 20 percent of the gateroad deteriorated in a markedly different fashion. These areas, defined "anomalous" zones, typically span several pillars. These areas usually depart from the norm in both the degree and kind of deterioration. For instance, one such zone in gateroad 1 suffered severe floor heave. This contrasted strongly with the majority of experience (e.g. figure 5). The nature of these zones is being investigated but appears to be influenced by local geologic features. They do not correlate with depth of overburden.

Some "noise" in floor ratings in the floor heave anomalous zone was initially confusing. Rehabilitation of this section had greatly reduced the apparent floor heave, resulting in lower ratings. However, the magnitude of heave remained apparent in the reduced opening height.



**Figure 6.** Deterioration ratings in the middle entry at the midpoint between crosscuts 11 and 12 in 2 North, an instrumented location, relative to the longwall face position.

The second gateroad, which will serve as a future tailgate as well as the present headgate, was developed with significantly larger pillars to withstand the combined pressure of panel and side gobs. The increase in pillar capacity might be expected to improve gateroad conditions. This was evident in index readings as the face passed, which reached a maximum value of 2, compared to 3 (see figure 6). What was not expected was that deterioration would be absent altogether in the roof while appearing in the floor. Heave occurred in the middle of the entry with passing of the longwall. It occurred in a manner appearing similar to buckling failure as illustrated in figure 7, after Rockaway and Stephenson (1979). This behavior was typical of about 80 percent of the second gateroad. Such pillar foundation failure is widespread in some regions (Gadde, 2009). This change in the pattern of deterioration, as well as the change in severity, would likely be a challenging modeling goal. However, if attained, it would be solid evidence that the model is well-tuned to mine ground conditions.

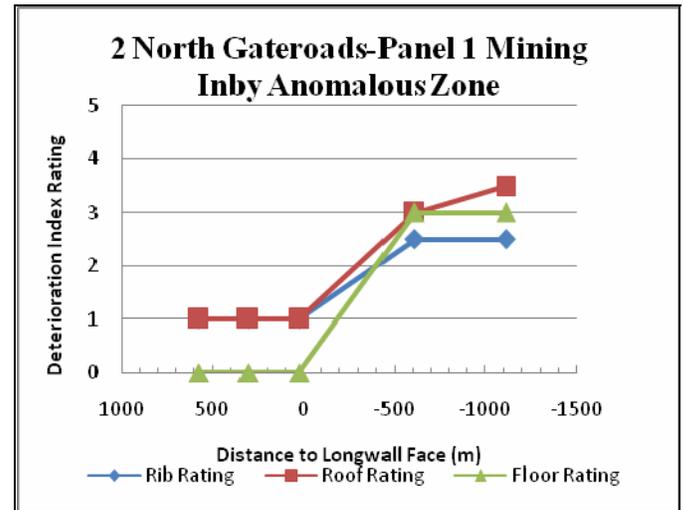


**Figure 7.** Buckling failure of the type observed in the 2 North gateroad (Rockaway and Stephenson, 1979).

Anomalous conditions were observed in two segments of the 2 North Gateroad, spanning several pillars, soon after passing the longwall face. Deterioration in these areas was further advanced and included the roof (figure 8). These segments appear to be associated with particular faults only. This association was not evident in the first gateroad.

These results show a rich detail in ground deterioration characteristics. Any correlation to overburden depth is not readily apparent, but may become evident with modeling. The abundance of anomalous deterioration zones points to the importance of good information on geology where it is variable and shown to impact deterioration. Wang and Heasley (2005) developed a method for combining a rating of geologic factors and stress model results as

inputs to a combined stability factor that could then be verified against deterioration surveys. Stewart et al. (2006a,b) describe application of this approach to anticipation of difficult roof conditions.



**Figure 8.** Deterioration ratings in the middle entry in the inby anomalous zone in 2 North, relative to the longwall face position.

#### SUMMARY AND RECOMMENDATIONS

The implementation of a ground condition mapping program, similar to that recommended in PIB 09-03, was successful in characterizing the ground response to mining in gateroads of a longwall coal mine. A number of details were refined, the most significant being definition of quantifiable measures appropriate to the mine and geologic setting. Defining these measures appropriately is critical to creating useful results. It is also important to separate data gathering from resulting decisions, such as the need for supplemental support.

In future ratings programs, four minor improvements might prove to be useful:

- First, recording rehabilitation efforts and installation of supplemental support installations may be useful. It is possible for ratings to improve through such measures, and we have encountered at least one instance of this. Indeed, such measures could be evaluated in this manner, primarily because such effects are likely to confound the model validation process unless properly recognized.
- Second, more frequent rating surveys are desirable. In this case, surveys were limited by investigator travel and availability.
- Third, integration of surveys into routine mining operations is desirable to provide more comprehensive data as well as warn when significant changes in ground response occur.
- Fourth, increasing the variety of simple objective measures and recordings could be useful and cost-effective if carefully targeted. These might include closure measurements, registered photographs, etc.

Results from these surveys are expected to be sufficient for model verification. A full understanding of the observed ground response, however, requires further work. One necessary step is the modeling described in P09-03, especially verification that matches model output quantities to the severity of deterioration and geology. Data like that collected here can also support two additional analyses. The first is to correlate deterioration to geology of the coal seam and immediate floor and roof strata. The abundance of anomalous ground deterioration zones, at roughly 20 percent of the gateroad length, is at least partially due to variable geology. Combining this information with stress modeling to form an expected conditions "index" (after Wang and Heasley, 2005) should be considered. The second is to investigate deterioration mechanisms as well as severity in a modeling program. A

better understanding of these mechanisms may provide additional insight into their safe and effective control.

Overall, the implementation of deterioration indices in the field has proven to be simple, inexpensive, and effective. They should be evaluated for use in any case where greater insight into the evolution of ground conditions during mining is desired.

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