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A Study on the Impact of In-Seam Rock Partings on Coal Pillar Strength Based on Field Instrumentation and Numerical Modeling at the Maple Eagle Mine

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ABSTRACT

In an effort to advance the science underlying modern coal pillar stability analysis, researchers at the National Institute for Occupational Safety and Health are currently involved in research aimed at better understanding the impact of an in-seam rock parting on the strength of coal pillars. The purpose of this study is to determine a suitable virtual mining height that could be applied using current pillar stability analysis tools. To accomplish this, the boundary element model LaModel was used to back analyze data collected on pillar performance in a room-and-pillar panel at the Maple Eagle Mine located in Southern West Virginia.

In a previous work, data collected from borehole pressure cells (BPCs) and extensometers were taken from three instrumentation sites. Data collected from the back bleeders were used to measure the rear abutment stresses, and data collected from two instrumentation sites in the wrap-around bleeder were used to measure the front and side abutment stresses as well as the peak strength and performance of the slabbed leave pillar. The utilization of two nearly identical instrumentation sites in the wrap-around bleeder provided much needed repeatability of the obtained measurements.

In this study, the data collected from BPCs at the three instrumentation sites was calibrated to match the Bieniawski pillar stress gradient. To model the measured pillar behavior, the LaModel program was selected due to its capability of being directly comparable to the Analysis of Retreat Mining Pillar Stability (ARMPS) and Analysis of Coal Pillar Stability (ACPS) programs. The model was then calibrated to match the measured abutment extent and abutment stress. Finally, the model was validated by reducing the modeled mining height until the yielding of the slabbed leave pillars in the model matched what was measured in the field.

The final calibrated mining heights show that a reduction of the shale parting thickness, not including any clay layers, of 52% is applicable. This research study provides the first known measurement of the ARMPS/ACPS "50% Rule" and its applicability to this panel of the Maple Eagle Mine. This finding provides a proof of concept and could have significant implications for future research.

INTRODUCTION

One of the primary challenges in underground coal mining is ensuring the stability of the mine structure, particularly the pillars that support the overlying strata. In the Central Appalachian region, the unique geological formations are complicated by factors such as varying depths of cover, geological anomalies, and the presence of in-seam partings. These complexities necessitate a thorough understanding of pillar behavior under different mining conditions as reserves with thicker parting, thinning coal seams, and challenging conditions are encountered.

Recent advancements in computational modeling, particularly the LaModel program, have provided researchers and engineers with tools to analyze pillar performance with greater accuracy. However, the calibration of such models remains a challenge, often requiring extensive field data and iterative adjustments. The importance of accurate model calibration cannot be overstated, as it can directly impact the safety of mining operations.

This study, conducted at the Maple Eagle Mine in Southern West Virginia, aims to bridge the gap between theoretical modeling and real-world pillar behavior. By leveraging state-of-the-art instrumentation and meticulous data collection, this research seeks to calibrate the LaModel program to the specific conditions of the Eagle Seam. Furthermore, the study delves into the intricacies of pillar behavior, exploring the impact of in-seam partings on coal pillar strength.

Historically, coal pillar design software such as the Analysis of Retreat Mining Pillar Stability (ARMPS) 2010 recommends a reduction of the entry height when competent rock is being mined. It specifically states that "the thickness of such 'cap rock' should be reduced by 50% (Mark, 2010)." The definition of what is considered competent rock, however, remains ambiguous.

In the sections that follow, a detailed account of the instrumentation strategy employed at the Maple Eagle Mine, the challenges faced during data collection, the calibration process of the LaModel program, and the insights derived from the analysis are provided. Through this comprehensive exploration, the aim of this study is to determine what, if any, of the in-seam parting can be considered competent and, therefore be applicable to the 50% Rule.

MINE LAYOUT AND GEOLOGY

The Maple Eagle Mine, situated in Southern West Virginia, extracts coal from the Eagle Seam at an average depth of cover of approximately 600 ft. over the designated study panel. The panel was designed as a nine-entry system with pillars spaced on 80-ft by 120-ft centers, resulting in a total panel width of 660 ft., excluding leave blocks. These are coal pillars that are developed but intentionally left in place during retreat mining.

Detailed near-seam geologic data was collected via underground measurements and borescoping at the study sites. The thickness of the in-seam parting in this area ranged from 51 to 52 in. but varied somewhat in its composition. Roof geology data obtained from a 20-ft. borehole indicated the first 13 ft. of immediate roof to be sandstone with the remaining 7 ft. deemed indeterminate due to the inability to clean the hole beyond this depth (See Figure 1). More detailed information on the mine layout and geology can be found in McElhinney, et al., 2023 which provides a robust foundation for this study.

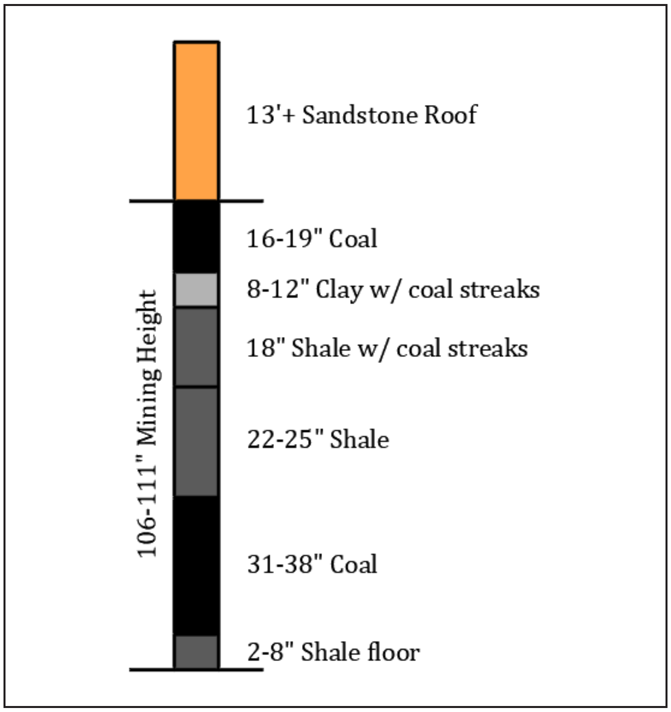

Figure 1. Coal section depicted as a composite of the measurements obtained from the study area (after McElhinney et al., 2023).

INSTRUMENTATION

Within the wrap-around bleeder system, three instrumentation sites were strategically positioned to measure the rear abutment loading, side abutment loading, and pillar performance (McElhinney et al., 2023). Site 1 was situated in the #4 entry, between crosscuts 30 and 31, at a depth of cover of 550 ft.

Sites 2 and 3 were placed in the #1 Entry, between crosscuts 20 and 21 and 18 and 19, with respective depths of cover of 400 ft. and 500 ft. (See Figure 2).

In this study, the focus of attention will be on the analysis of data collected from borehole pressure cells (BPCs) installed at the three distinct field sites. The data gathered from these BPCs will be instrumental in understanding the pillar performance in the mine. The use of extensometers, while part of the broader instrumentation strategy, will not be discussed in this paper. For detailed information on the instrumentation used and best practices for installation see Minoski et al. (2024) and McElhinney et al. (2024).

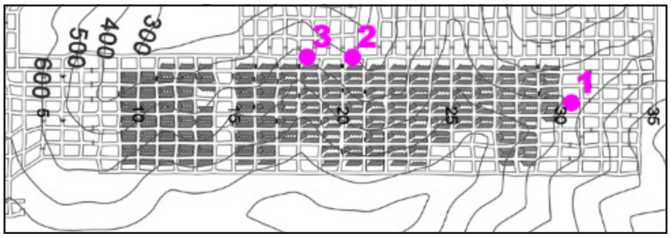

Figure 2. 14-2 Belt panel layout showing the location of the three instrumentation sites labeled 1, 2, and 3 including overburden contours (after McElhinney et al., 2023).

The instrumentation at Site 1 was set up a week before retreat mining began. This site featured six borehole pressure cells (BPCs) strategically placed within the #4 entry pillar. Despite some drilling challenges, the BPCs were installed at varying depths to ensure redundancy and comprehensive measurements. The BPCs were pressurized to an average of around 1,300 psi. Additionally, three roof extensometers were installed across the opening between BPCs 4 and 5 (See Figure 3).

Site 2, located between crosscuts 20 and 21, was equipped with six BPCs. Due to rib sloughing and equipment placement, BPCs were installed at varying locations along the pillar and at depths of 15 and 25 ft. The BPCs at Site 2 were pressurized to an average of approximately 1,700 psi to account for pressure bleed-off experienced at Site 1 (See Figure 4).

Site 3, positioned between crosscuts 18 and 19, was designed to replicate the results obtained at Site 2. Despite some equipment issues and borehole squeezing, the site was equipped similarly to Site 2. The BPCs at Site 3 were pressurized to an average of approximately 2,000 psi to account for anticipated bleed off. Despite minor deviations, Site 3 remained fit for its intended purpose (See Figure 5).

INSTRUMENTATION RESULTS

The borehole pressure cells (BPCs) at Site 1 exhibited typical behavior, with initial pressure bleed-off followed by stabilization.

Upon the start of retreat mining, the pressure began to increase rapidly, then slowed down as the panel squared up. BPCs 1 and 2 experienced a pressure drop during mining, likely due to borehole breakage. BPCs 1 and 6, installed 10 ft. into the pillar, showed different responses, possibly due to the initial load shedding event. BPCs 3 and 5, installed 17 ft. into the pillar, also showed different responses, the reason for which remains unclear (see Figure 6).

At Site 2, the BPCs showed a similar performance pattern to Site 1, but with lower and more gradual bleed-off

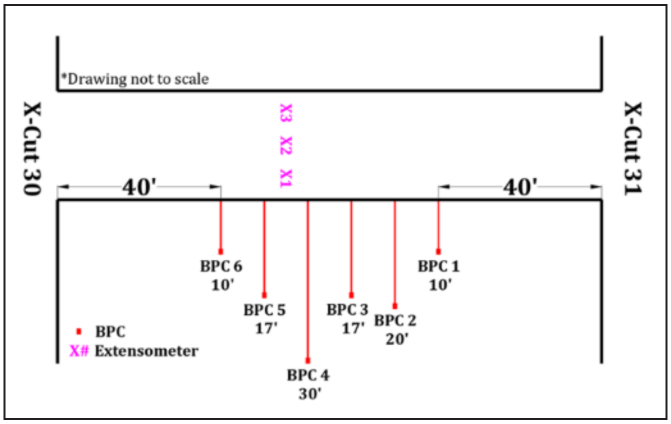

Figure 3. Instrumentation layout for Site 1 installed from the #4 entry (after McElhinney et al., 2023).

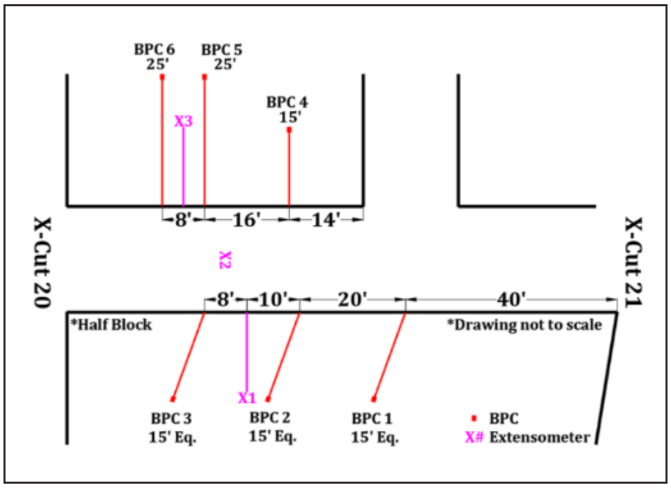

Figure 4. Instrumentation layout for Site 2 installed from the #1 entry (after McElhinney et al., 2023).

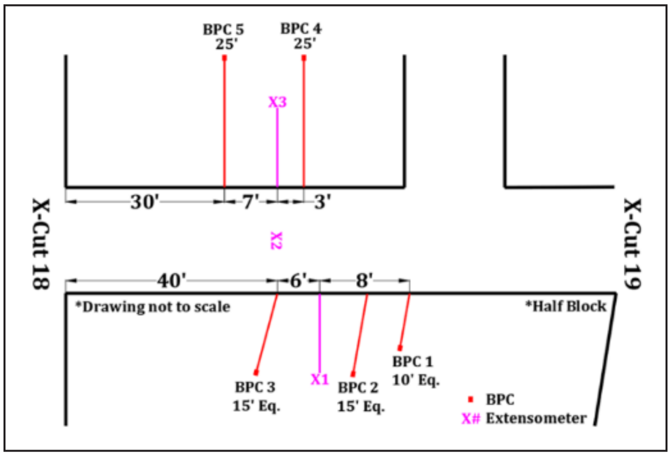

Figure 5. Instrumentation layout for Site 3 installed from the #1 entry (after McElhinney et al., 2023).

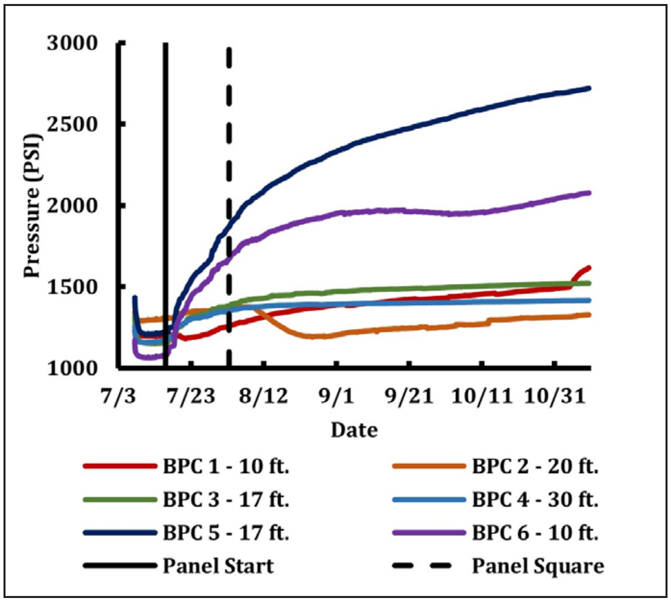

Figure 6. BPC data collected from Site 1 with the solid black line indicating the retreat mining start date and the dashed black line indicating the date when the panel was approximately squared up (after McElhinney et al., 2023).

from the setting pressure. The onset of sustained BPC pressurization began when mining was nearing completion of the row directly inby the instrumentation site. Significant pressurization began when slabbing of the instrumented pillar began. Once the peak stress in the pillar was reached, the pillar exhibited strain-softening behavior and began to shed load onto the adjacent abutments (see Figure 7).

Site 3 showed similar performance to Site 2, with some additional loss of data due to presumed damage to the instrument or wiring. The onset of initial movement was more difficult to determine here. However, all installed BPCs began to show sustained pressurization when mining was closing out in the row inby the instrumentation site. A significant pressure increase began when active mining of the instrumented pillar began. Once the peak stress in the pillar was reached, the pillar began to shed load onto the surrounding abutments (See Figure 8).

Based on the data collected from Sites 2 and 3 indicating the arrival of the front abutment loading, the abutment distance was measured to be approximately 200 ft. Taking the timing of the average peak pressure for the two pillars, respectively, indicated that pillar yield began when the pillar line was approximately 290 ft. outby the instrumentation site (see Figure 9). Having provided a comprehensive summary of the data collected from the three sites, we now

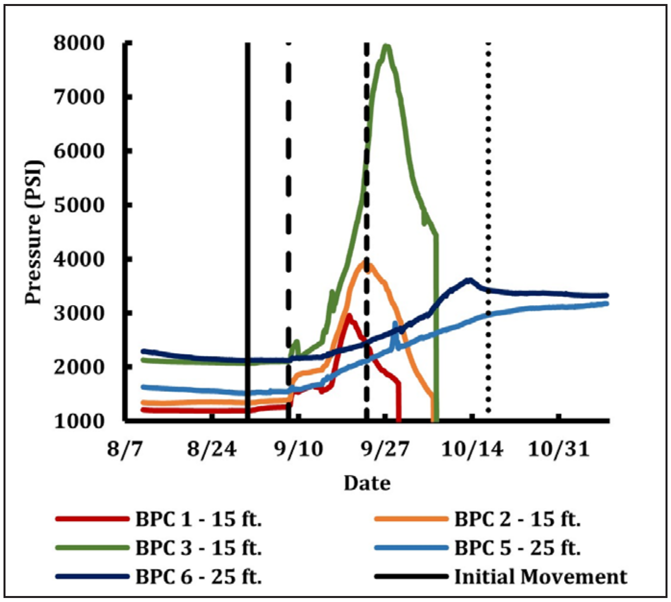

Figure 7. BPC data collected from Site 2 during retreat mining where the solid black line indicates initial movement, and the increasingly smaller dashed lines indicate slabbing of the instrumented pillar, the peak stress, and the near completion of load shedding, respectively (after McElhinney et al., 2023).

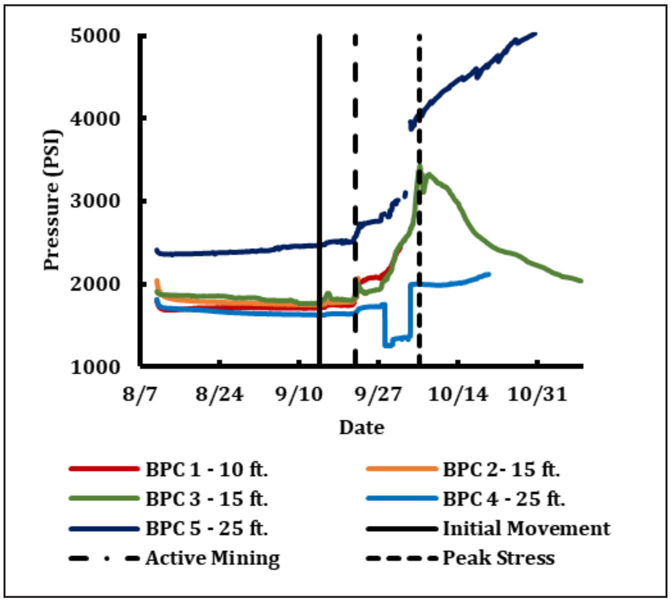

Figure 8. BPC data collected from Site 3 during retreat mining where the solid black line indicates initial movement, and the increasingly smaller dashed lines indicate slabbing of the instrumented pillar and the peak stress, respectively (after McElhinney et al., 2023).

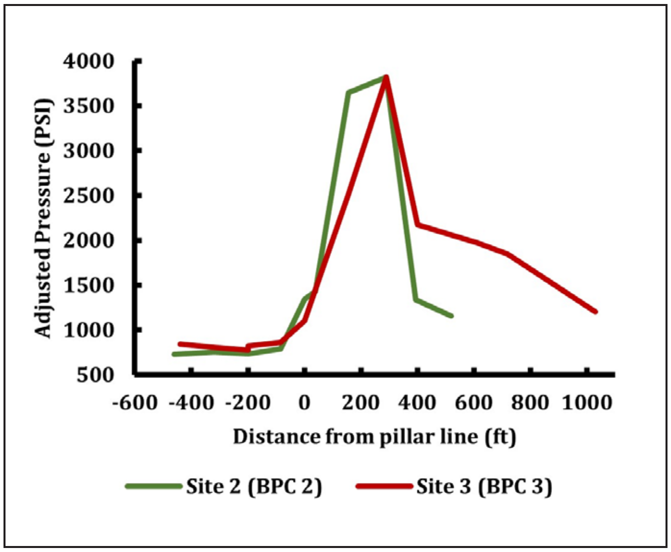

Figure 9. Average BPC pressure for Sites 2 and 3 versus the distance from the pillar line depicting the arrival of the front abutment load, the peak pressure measured in the pillar, and pillar yield.

turn our attention to the next crucial step in our study: calibrating the LaModel program to accurately represent and further analyze the collected data.

BUILDING THE MODEL

The LaModel 3.0 program was selected to model the measured pillar behavior because its calibration procedures are considered to be directly comparable to the widely used ARMPS 2010 (Mark, 2010) and ACPS (Mark and Agioutantis, 2018) programs.

Utilizing LAMPRE 4.0, the preprocessor software for LaModel, the coal seam was discretized using 5-ft. elements (See Figure 10). A grid size of 1,200 x 800 elements or 6,000 x 4,000 ft. was selected to provide an ample buffer against any potential edge effects. Boundary conditions were modeled as symmetric on all sides.

The overlying overburden was discretized using 50-ft. elements. A grid size of 160 x 120 elements or 8,000 x 6,000 ft. was selected resulting in a 1,000-ft. buffer around the underlying seam grid. An overburden grid that is larger than the seam grid is required in LaModel, and one that is more than the overburden thickness away from the edge of the seam grid reduces edge effects from the projection of the overburden grid to the seam level.

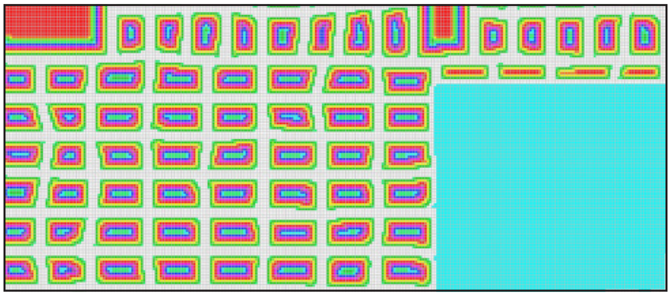

Figure 10. Portion of the seam grid generated in LaModel including pillars, openings, and gob areas.

CALIBRATION OF THE MODEL

It is well established that the calibration of input parameters for numerical models is of vital importance. In the context of conducting a LaModel analysis, it is imperative to note that the precision of the output is directly related to the accuracy of the input parameters. These parameters should be calibrated utilizing the most reliable data sources, which could be measurements, observations, or empirically derived. The critical parameters for accurate stress and load calculations, and consequently pillar stability and safety factors, are the rock mass stiffness, the gob stiffness, and the coal strength. The parameters must be calibrated in the order listed, with each subsequent parameter's calibrated value determined by the preceding ones (Heasley, 2008).

In the LaModel framework, the stiffness of the rock mass is characterized by two key parameters: the rock mass modulus and the lamination thickness (see Figure 11). By adjusting these parameters, one can effectively alter the stiffness of the overburden, which in turn affects the abutment extent. In the context of this study, the rock mass modulus was held constant at a value of 3,000,000 psi. The lamination thickness, on the other hand, was adjusted to align with the measured abutment extent. To match the measured 200-ft. abutment extent at the edge of the panel, a lamination thickness of 90 ft. was found to be necessary. The calibrated lamination thickness is approximately 25%

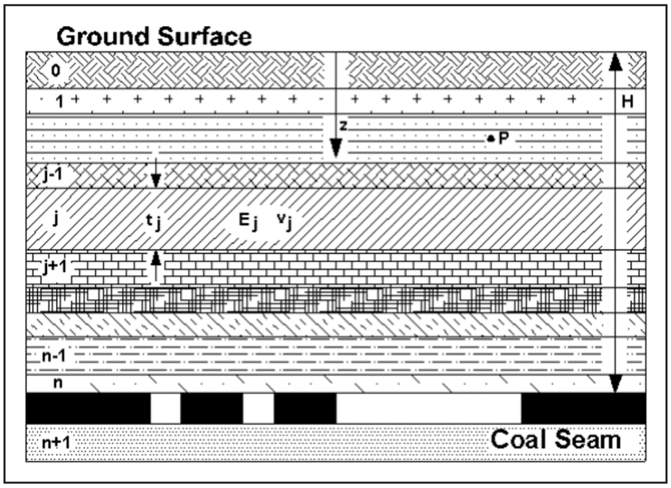

Figure 11. Overburden layers indicating thickness, modulus, and Poisson's ratio.

less than what is empirically suggested using the lamination thickness wizard.

The calibration of the gob stiffness, which is based on borehole pressure cell (BPC) measurements, necessitated the identification of an appropriate calibration technique for the BPC data. Over the years, numerous attempts have been made to correlate measured BPC data with the actual stress in the rock mass. These attempts have been documented by various researchers (Sellers, 1970; Bauer et al.,1985; Babcock, 1986; Heasley, 1989; Su and Hasenfus, 1990). Two significant factors that influence the response of BPCs are the setting pressure and the stiffness of the material in which the BPC is installed. Given that the BPCs used in this study had varying setting pressures and most were installed in the rock parting, it was deemed crucial to employ a calibration procedure that was suitable for this specific context.

To address this challenge, the BPC data was calibrated using a secondary, empirical data source. This calibration method, which is a variant of the work conducted by Tulu and Heasley (2012), makes the assumption that the peak stress in the pillar at the location of the yielded BPC aligns with what is expected based on the Bieniawski pillar stress gradient (Mark and Chase, 1997). The percentage increase of the measured value versus the expected value can then be used as a calibration factor for the remaining BPCs that did not yield (see Tables 1 and 2). This BPC calibration technique was selected so that the BPC measurements could be directly related to the results from either ACPS or LaModel.

As can be seen from Table 2, the expected abutment loading for the side abutments is 3.1 times the development load. For the back bleeders, an average of 2.6 times the development load over the instrumented area is expected. These values can now be used to calibrate the LaModel program based on the expected abutment loading compared to what was measured in the field.

Table 1. Measured and expected stress for the four BPCs that reached their peak pressure in the half leave pillars indicating an average BPC calibration factor of 1.6.

	% Increase Over Development Load				
BPC	1	2	3	4	Avg.
Measured	249%	296%	384%	195%	281%
Expected	440%	440%	440%	440%	440%
Cal. Factor	1.8	1.5	1.1	2.3	1.6

Table 2. Measured and expected stress for the three BPC locations where sufficient data was recorded in the abutment pillars at Sites 2 and 3 labeled S1, S2, and S3 and the average for all BPC data collected from Site 1 labeled Bld.

	% Increase Over Development Load				
BPC	S1	S2	S3	S-Avg.	Bld.
Measured	209%	170%	214%	198%	164%
Expected	327%	266%	335%	310%	257%

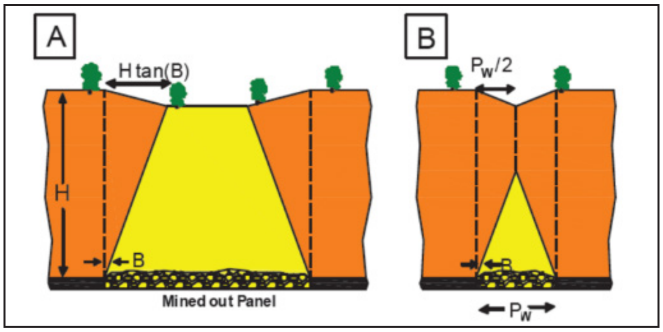

Figure 12. Conceptualization of the abutment angle depicting a supercritical panel (A) and a subcritical panel (B) (after Mark, 2010).

The final gob modulus defines the stiffness of the strain-hardening gob material and controls the magnitude of the abutment load. This is typically conceptualized using the abutment angle (see Figure 12), where stress measurements from five mines suggested an average of 21° in U.S. mines (Mark, 1992). The final gob modulus that best matched the calibrated BPC measurements of the abutment loads was found to be 460,000 psi. This is equivalent to an abutment angle of approximately 29–30°. While this is significantly higher than the average, it falls within the range of measured cases, particularly at shallow cover depths of less than 600 ft.

The coal strength calibrated for the initial model assumed the pillars were 9-ft. high, as measured at Sites 2 and 3. The Mark-Bieniawski pillar strength, assuming a 900-psi in-situ coal strength, was used to simulate the coal material using an elastic-plastic material model. This model was chosen due to its widespread understanding compared to the calibration process involving strain-softening materials. It matches the Mark-Bieniawski pillar strength without calibrating the in-situ coal strength, which is a function of pillar size for strain-softening materials.

THE VIRTUAL MINING HEIGHT

Based on the results of the initial calibrated model, it was determined that the half-yield block reached its peak strength when the pillar line was 170 ft. outby the instrumentation site. However, measurements obtained clearly indicate that the pillar reaches this point in reality when the pillar line is 290 ft. outby. Therefore, the strength of the pillar required an adjustment to align with the measurements taken in the field.

As mentioned previously, modern coal pillar design software provides an allowance for this type of scenario. The guidelines from ARMPS 2010 specify that "A special case might be a thick parting that includes some strong rock. In that case, the strong portion of the parting could be subject to the '50% rule' described above. A geologist or ground control professional could help determine how much of the parting is actually competent rock (Mark, 2010)."

To determine a suitable 'virtual mining height' for this case study, the modeled mining height was reduced from 9 ft. in the original calibrated model to match the timing of the peak stress measured in the field at Sites 2 and 3. This allowed for the determination of the reduction in mining height that is applicable in this case and, therefore the amount of the in-seam parting that could be subject to the 50% Rule. This adjustment also necessitated a recalibration of other primary input parameters, such as lamination thickness and gob modulus, based on the new mining height.

For Site 2, it was determined that a virtual mining height of 7.5 ft. best matched the measured borehole pressure cell (BPC) data. This necessitated the use of a lamination thickness of 110 ft. to obtain the measured abutment extent. The change in overburden stiffness relative to seam stiffness required a final gob modulus of 470,000 psi to achieve the same abutment loading.

For Site 3, the mining height had to be further reduced to 7 ft. to best match the measured BPC data. This required the use of a lamination thickness of 120 ft. to obtain the same measured abutment extent. This additional change in overburden stiffness necessitated the input of a final gob modulus of 480,000 psi to achieve the same abutment loading.

RESULTS

The results obtained from the calibrated model after adjusting the virtual mining height to calibrate the pillar strength were compared to the Bieniawski-adjusted BPC data collected at Sites 2 and 3. At Site 2, data collected from BPC 2 was used as a near-average representation of the data collected from the three BPCs. From Site 3, only the data collected from BPC 3 was suitable for comparison (See Figure 13).

From Figure 13, it is apparent that there is excellent correlation between both the measured and modeled data for both sites. Given that Site 3 was intended to provide for repeatability of results, it is clear that this was achieved. Although not shown in the figure to reduce clutter, an exact match for three out of the four BPC measurements was obtained.

Additionally, from this comparison, it is clear that a 7.5-ft. mining height was appropriate for modeling Site 2, and a 7-ft. mining height was appropriate for modeling Site 3. This resulted in an average reduction of the shale parting thickness, discounting the 8 to 12 in. of clay and any floor rock, at each site of 52% (See Figure 14).

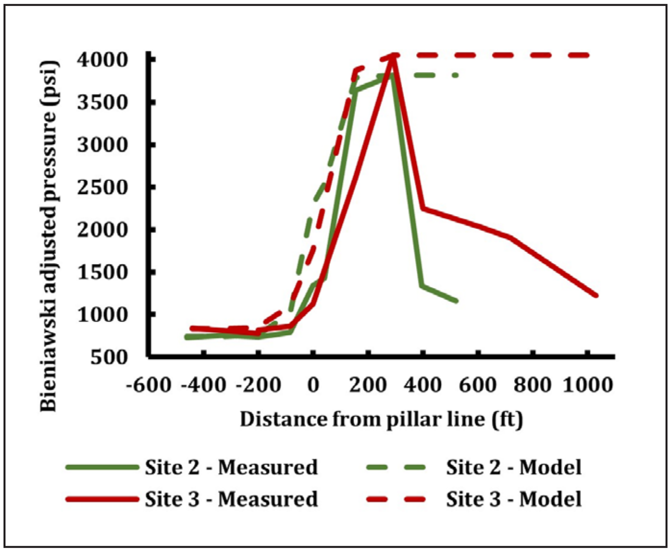

Figure 13. Average BPC pressure for Sites 2 and 3 for both measured data (solid line) and model results (dashed line) versus the distance from the pillar line.

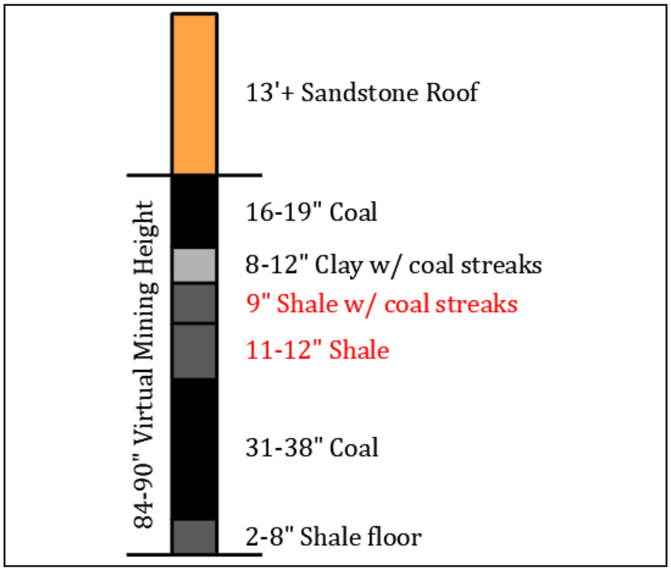

Figure 14. Composite coal section modified from Figure 1 to depict the virtual mining height resulting from a 50% reduction in the shale parting thickness labeled in red.

CONCLUSIONS

This comprehensive study, conducted at the Maple Eagle Mine in Southern West Virginia, has provided valuable insights into the behavior of pillars and the calibration of the LaModel program. The following conclusions can be drawn:

Instrumentation and Data Collection: The strategic placement of borehole pressure cells (BPCs) at three different sites within the mine as detailed in McElhinney et al., 2023 allowed for a detailed understanding of pillar performance. The data collected from these sites was instrumental in calibrating the LaModel program, providing a robust foundation for further analysis.

Model Calibration: The calibration of the LaModel program involved meticulous adjustments of critical parameters such as Rock Mass Stiffness, Gob Stiffness, and Coal Strength. The alignment of these parameters with the measured data ensured the accuracy of the stress and load calculations.

Virtual Mining Height Adjustment: The adjustment of the virtual mining height to match the timing of peak stress measured in the field was a critical step in the calibration process. The reduction of the mining height to 7.5 ft. for Site 2 and 7 ft. for Site 3 resulted in an average reduction of the shale parting thickness of 52%—which means that the "50% Rule" is applicable for the shale parting observed at these sites.

Model Results and Correlation: The calibrated model exhibited an excellent correlation with the measured data from Sites 2 and 3. The repeatability of results between these sites further validated the model's accuracy.

In summary, the research conducted in this study represents a significant contribution to the field of pillar design and numerical model calibration. This study represents the first successful measurement of the "50% Rule" and the impact of a thick in-seam parting on pillar strength. The insights gained from this study not only enhance our understanding of pillar behavior but also pave the way for future research and innovation in mine safety.

LIMITATIONS AND FUTURE RESEARCH

The primary limitation of this study is the limited scope of potential application, because this study reports on site-specific findings, the findings may not be directly applicable to mines with different geological conditions. Research is ongoing at the mine to take a second measurement of the pillar performance in a subsequent panel where the in-seam parting is thinner and apparently weaker.

Additional limitations refer to assumptions made in the study, such as the alignment of the peak stress in the pillar with the expected values from the Bieniawski stress gradient. While this assumption currently represents our most thorough understanding of pillar strength and assists with making comparisons to modern pillar stability analysis tools, it might not hold true in all mining scenarios, limiting the applicability of the calibration method.

Finally, the study refers to the ambiguity in defining what is considered competent rock. This ambiguity could lead to variations in the application of the "50% rule." This could impact the replicability of the study in different contexts, mining scenarios, and geologic conditions.

Future research in relation to the "50% Rule" and the impact of in-seam parting on pillar strength would be required to address these limitations. This should include additional field sites to measure pillar performance with a range of geologic conditions including rock thickness and strength. Additional data should be collected on the strength of the parting itself to better define what should and should not be considered competent rock. Research such as this would provide engineers with a much more broadly applicable tool for assessing the strength of coal pillars as more mines experience significant out-of-seam dilution and are mining more rock.

In conclusion, while the study provides valuable insights into the behavior of pillars in a specific mining context, the limitations must be considered when applying the findings to other scenarios. The implications for future research highlight exciting opportunities for further exploration and development in the field of coal pillar design.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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A Surface Geotechnical In-Pit Underground Portal Relocation: An Operations-Based Case Study

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ABSTRACT

Reactivation of highwall slope failures during adverse weather had intermittently impacted haul road access into a previously mined open pit. These impacts ranged from limited access to full closures; however, the greater impact was to an underground mine that was developed within the open pit. Following several significant precipitation events, a rapid snow melts greatly accelerated movements finally closing the haul road and destabilizing other past failures. In addition to re-designing the overall pit access, the decision was made to relocate the primary portal to a more stable highwall. An accelerated surface geotechnical review was required to advance the portal relocation; however, only existing information from past investigation, existing geology model, visual inspections, and slope monitoring data were available for the assessment - no new investigations or data collection could be completed within the allowable timeframe. The evaluation included a review of the geology, an assessment of the current highwall condition and previously observed performance, and a rockfall analysis to evaluate existing catchment above the proposed new portal location.

BACKGROUND

The mine operation discussed in this operational case study is in northern Nevada, USA. Although gold mineralization associated with this deposit was identified in the 1960s, surface mining did not begin until 2004. The open pit was mined in 5 separate, adjacent phases from 2004 until the completion of the final layback in late 2010. Immediately following completion of surface mining, development for an underground portal operation began in December 2010 in the northern end of the pit floor.

The most significant open pit slope instability occurred during the second layback, or phase, which encompassed the southernmost portion open pit slope. Active mining of this phase occurred between 2005 and 2007. The southern highwall was established within a structural zone bound by two defined, typical basin and range faults. In 2006, the region experienced above average spring precipitation which adversely affected highwall stability. The natural topography and run-off essentially drained toward the open pit slope. This highwall proved to be sensitive to rainfall, snow melt, and run-off in the years following mining activity. The south pit slope exhibited continued slope failure after underground operation commenced, during wetter than normal Spring months. These internal failures would impact a laydown yard that had been developed below the pit slope. Remediation activities generally required relocation of materials and equipment, cleaning back of failure material, and building larger containment berms.

Throughout mining of subsequent phases, the pit slope generally performed very well; no significant slope failures that impacted mining activity were observed. There were some local bench-scale failures in the upper most benches which were established in weathered Vinnini Fm. or Rodeo Creek Fm. that were managed with clean-up or contained on existing benches.

However, in December 2015, slope instability began to develop in the west highwall of the final open pit phase (see Figure 1). A slope failure of the lower extent of the highwall impacted the use of the batch plant. Crest displacement included the pit side outer portion of the haul road/access road into the pit.

The slope movement impacted the available width of the haul road. Access was narrowed to signal lane by berming the outer edge. Furthermore, the observational geotechnical risk mitigation approach outlined in a site specific, standard operating procedure (SOP) and trigger action response plan (TARP) specified that depending on