PROCEEDINGS OF THE 43rd International Conference ON GROUND CONTROL IN MINING

ICGCM 2024

Edited by

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ebook ISBN 978-0-87335-516-2

A Case Study of Path Dependent Calibration and Pillar Stability Analysis Using the LaModel Program

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ABSTRACT

The LaModel program is widely used to calculate stresses and displacements on thin tabular deposits, particularly when multiple seams or complex mining geometry is encountered. The program itself allows the user to create multiple mining steps to show a progressive sequence of mining. However, LaModel considers each individual step as an independent steady-state condition, and any previous loading conditions of the materials are not tracked. It also does not consider any sort of dynamic stress change during the mining process. In certain circumstances, especially in multiple-seam situations, modeling a scenario of the seam of interest without considering the previous mining sequence in the off seams can potentially lead to inaccurate results.

The primary objective of this paper is to present a situation where a potentially dynamic, unstable mining condition was encountered. It was not evident until the previous loading conditions in the off seams and the impact of dynamic stress changes in the active seam were considered. It is important to make the mining community aware of these potential modeling scenarios where the path-dependent nature of the mining sequence is of key importance.

This paper presents a case history where room-and-pillar retreat mining was being conducted in a relatively deep cover stress regime where multiple seam interactions were present from both undermining and overmining. Mining in the active seam was being conducted with room-and-pillar mining techniques consisting of a series of parallel production panels being successively developed and retreat mined along a set of Mains. In this situation, the traditional global LaModel analysis without any path-dependent adjustments did not fully identify the area of poor conditions that were encountered.

This paper explores the impacts of mining in the active seam on the lower seam which, in turn, has a negative impact on the active seam. This provided a solid foundation for the subsequent analysis of the three seams simultaneously. Based on the calibrated model, it is likely that retreat mining in the active seam resulted in increased stresses in the underlying seam that conceivably resulted in additional convergence and, most likely, additionally convergence of the pillars under the panel being developed. This in turn could have caused active subsidence, squeezing of the pillars, floor heave, and significant rib deterioration in the active workings.

The LaModel program is extremely useful for analyzing multiple-seam mining scenarios. As multiple-seam situations become even more prevalent, the potential for encountering a path-dependent mining scenario also increases. To successfully model path-dependent mining scenarios, the ground control engineer will be required to make sound judgments on the condition of pillars in sub-adjacent seams. These engineering judgments should be based not only on the current state of stress, but also on any prior or future states of stress. This means considering the stresses from over or undermining as well as stresses applied to the sub-adjacent seams from actively mining the seam of interest.

INTRODUCTION

The study mine produced coal from the No. 2 Gas seam in Southern West Virginia. In the study panel (See Figure 1), the parting between the upper and lower 2 Gas splits thickens, resulting in a mining height approaching 10 ft (see Figure 2) and a depth of cover ranging from about 700 ft. to 900 ft. across the panel.

The Eagle seam has been mined with both longwall and room-and-pillar methods 205 ft. beneath the overlying 2 Gas seam with room-and-pillar methods employed directly underneath the area of interest. The mining height of the Eagle seam was typically 7 ft. where longwall mining had occurred and a thinner 5.5 ft. where room-and-pillar methods were used. The overlying Williamson seam (250 ft. above) was mined using room-and-pillar methods and the mining height in the area of interest was approximately 4.5 ft (See Figure 3).

On Nov. 4th, 2014, active mining in the study panel was terminated and both internal and external investigations had begun by Nov. 14th to determine the cause of an extensive amount of rib damage that was noted on the left-hand side of the section, the area adjacent to both an underlying Eagle seam gob/solid boundary and an

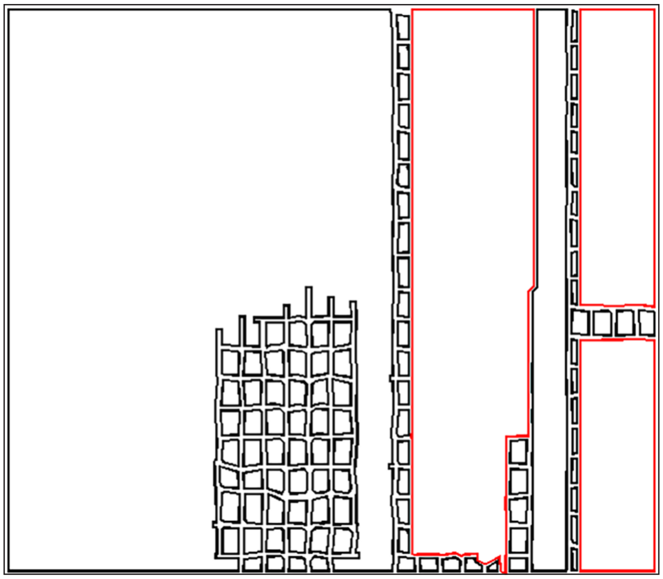

Figure 1. Study production panel located adjacent to previously retreat mined panels in the active 2 Gas seam

Figure 2. Photo depicting the thickness of the in-seam parting as well as showing conditions typical of the right-hand side of the study panel

overlying Williamson seam gob/solid boundary. During this initial investigation, it appeared that, based on the amount of seismicity that was observed in both audible and felt vibrations, what was occurring was more significant than typical multiple seam stress conditions observed in the past at this mine. The sounds and vibrations occurring were more typical of a retreat section during caving than it was of a development section. On Dec. 3rd, 2014, the observations and measurements were taken for the last time prior to the panel being abandoned and sealed. In that time frame, additional stress-related features were observed, particularly in the #4 entry near the face. In this area, some additional rib damage had occurred (see Figure 4), and an additional 15 in. of floor heave was measured (see Figure 5). However, no additional roof sag was measured from a telltale (Bigby, 2001) installed in the roof, and the Nos. 5–7 entries still looked like that depicted in Figure 2.

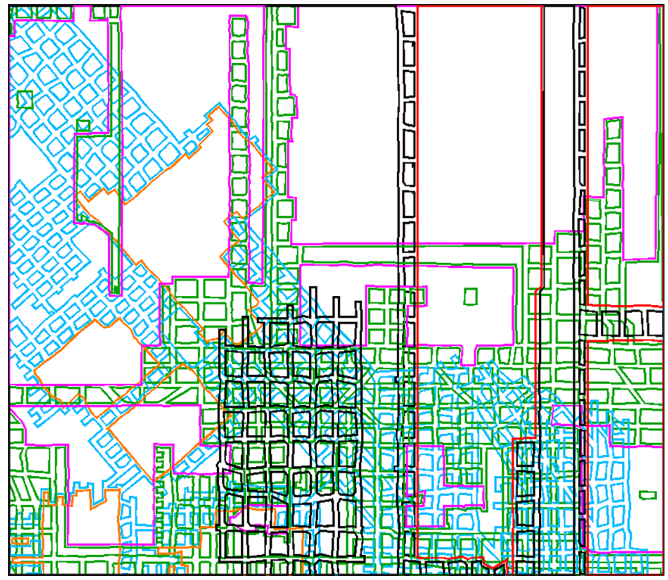

Figure 3. Final map depicting the active 2 Gas seam workings with black pillars and red outlined gob areas, Eagle seam workings with green pillars and magenta outlined gob areas, and Williamson seam workings with blue pillars and orange outlined gob areas

Figure 4. Photo taken on Dec. 3rd, 2014, depicting rib sloughage with a broken post indicating additional convergence

During this thorough investigation, multiple theories as to why this relatively extreme amount of deformation was being observed in an area where it was not expected. After all, the mine had successfully developed and retreat-mined in areas of theoretically higher stress. One of these potential explanations was that retreat mining in the previous panel placed additional stresses on the pillars in the underlying Eagle seam causing those pillars to then fail and cause active subsidence of the study panel. To determine how likely this scenario was, the widely used LaModel program (Heasley, 1998) was selected due to its potential to be directly comparable to the AMSS (Analysis of Multiple Seam Stability) and ACPS (Analysis of Coal Pillar Stability) programs (Mark et al., 2007; Mark and Agioutantis, 2018).

MAPPING

A LaModel analysis is only as accurate as the input information used to create the model. Mapping of the adjacent and over/underlying seams appeared to be fairly accurate based on previous mining experience and encounters with multiple seam stresses in the 2 Gas seam. However, a discrepancy in the survey locations of a gas well near the outcrop of the overlying Williamson seam was discovered during this extensive re-analysis of the study panel pillar stability. While it is not a guarantee that mapping and subsequent digitizing of the overlying mine is off by a linear distance of 158 ft., as was surveyed, it did raise some concerns as to the accuracy of the mapping involved. At this point, it was decided to linearly adjust the overlying Williamson seam workings by 158 ft. to match the location of the GPS surveyed gas well (See Figure 6).

Figure 5. Area where 15 in. of floor heave was measured showing bent pogo stick

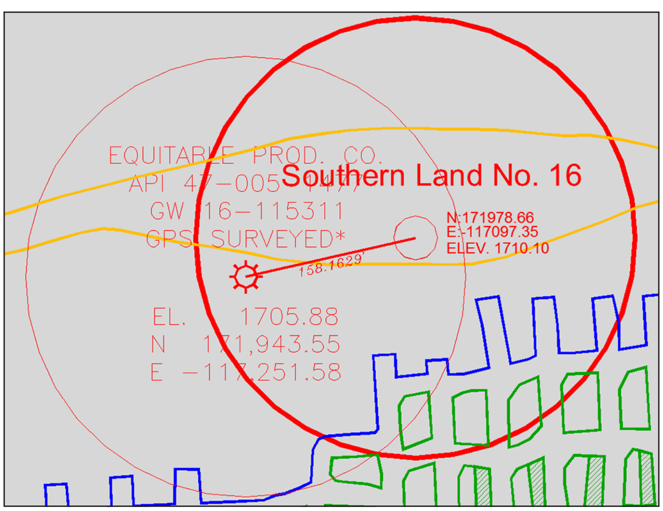

Figure 6. Gas well location based on GPS coordinates and mine coordinates

MINING SEQUENCE AND INPUT PARAMETERS

Traditionally, large-scale global models are used to determine multiple seam influence over a large area for planning purposes. For this re-analysis, a smaller model area of 2,300 ft. x 2,000 ft. was discretized using 5-ft. elements to create seam grids for the three seams of interest. A mining height of 9 ft. was chosen for the 2 Gas seam. Modeled mining heights for the Eagle and Williamson seams were 5.5 ft. and 4.5 ft. respectively.

The calibration of input parameters is crucial for the accuracy of numerical models, a fact that is widely acknowledged in the scientific community. In LaModel, 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. These parameters must be calibrated in the order listed, with each subsequent parameter's calibrated value determined by those preceding it (Heasley, 2008).

In LaModel, the lamination thickness is used to control the rock mass stiffness, and therefore the abutment extent. Rather than use the empirically suggested abutment extent (Mark and Chase, 1997), a reduced lamination thickness is typically required to accentuate the multiple seam stresses. Sears and Heasley (2013) utilized a consistent 50-ft. lamination thickness in the analysis of multiple-seam pillar failures under shallow cover. However, in relatively deep-cover mines such as those in the Eagle and 2 Gas seams, a lamination thickness of 100 ft. has been generally accepted by the LaModel practitioners' community and was chosen for use in this model.

The final gob modulus defines the stiffness of the strain-hardening gob material and controls the magnitude of the abutment load and, consequently, the multiple seam stresses. Even though only 3 Seams are used in this analysis, a total of 5 gob moduli were calibrated based on the empirically suggested 21-degree abutment angle (Mark, 1992). A gob modulus of approximately 491,000 psi was used for the 2 Gas seam, while a gob modulus of approximately 1,076,000 psi was used for the Williamson seam. The remaining three gob moduli were calibrated and used for the Eagle seam depending on the associated average gob width and depth, particularly in the area directly underlying the termination point of the study panel.

For the wide, deep Eagle seam gobs, a modulus of about 232,000 psi was required where the narrower, deep gobs required a modulus of approximately 381,000 psi to match the empirically suggested abutment extent. Finally, some of the shallower gob areas required a final gob modulus nearly equal to the modulus used for the Williamson seam gob areas.

Finally, coal materials in the model were created using the material wizard in LamPre3.0, the pre-processor to LaModel. Each seam was given a set of elastic-plastic material properties based on the Mark-Bieniawski coal strength (Mark, 1992) given their respective mining heights.

ANALYSIS

The first step in the comprehensive reanalysis of the study panel was to create a series of mining steps where the preceding panel was developed but not yet retreat mined. The subsequent step, 2,

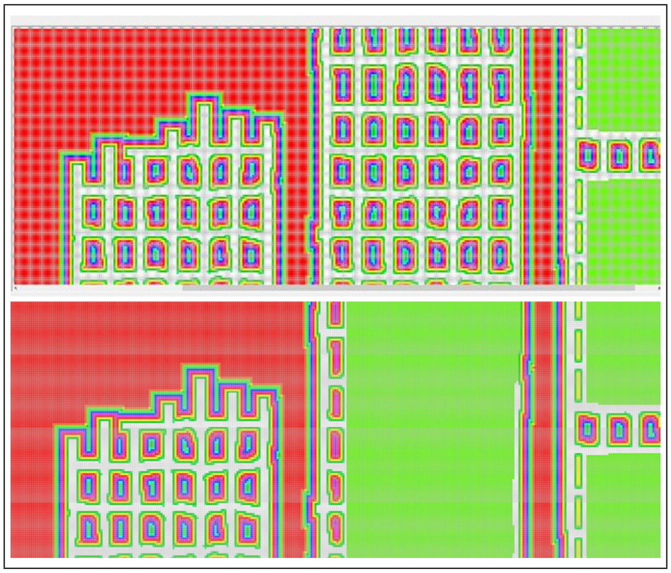

Figure 7. LaModel seam grids for Step 1, development of both study and preceding panel (top), and Step 2, retreat mining of the preceding panel

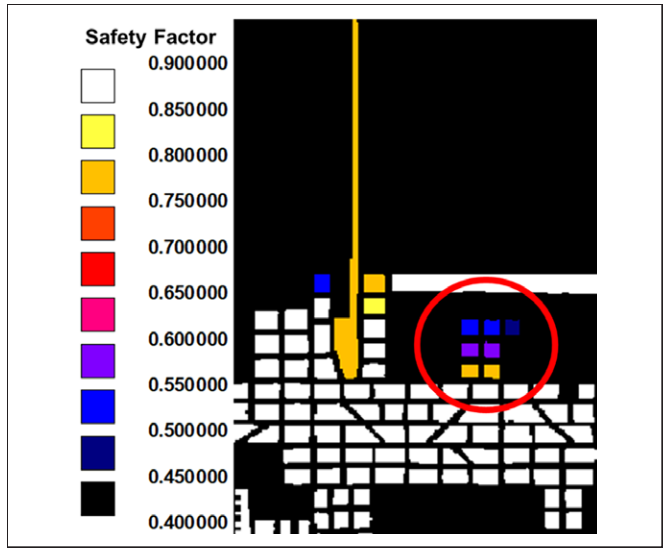

Figure 8. Pillar stress safety factors for the underlying Eagle seam prior to retreat mining the preceding panel in the active seam

then shows the retreat mining of the preceding panel where one can then observe the impacts of this abutment loading on the Eagle seam (see Figure 7).

The results of Step 1, prior to mining of the preceding panel, show that the pillar stress safety factors of the seven pillars are left directly under the barrier pillar of the study panel near its termination point range from about 0.5 to 0.8 (See Figure 8). Additionally, one can see that several pillars or pillar rows to the north have also failed as indicated by the area within the red circle.

The results of Step 2, after retreat mining, show that the safety factors of the seven pillars left in the underlying Eagle seam now range from just below a 0.5 to less than a 0.7 and are highlighted by a red circle (See Figure 9).

By looking at the differences between Step 1 and Step 2, it is clear that there could potentially be some additional convergence of the Eagle seam by retreat mining the preceding panel in the active seam. While the stability of the three pillars initially at a SF of about 0.5 is debatable, undoubtedly an additional load applied to these pillars as well as the ones in the 0.6–0.8 range by as much as 20% could be significant and has potentially caused the remainder of these pillars to yield and shed their remaining load-carrying capacity.

At this point, it was safe to assume that the remaining seven pillars in the Eagle gob directly underlying the right side of the study panel and barrier had completely yielded and that the width of the gob for that portion of the Eagle seam would require recalibration. This resulted in changing the gob modulus for that panel in the Eagle seam to about 289,000 psi. Plots of the Multiple Seam Stress and the In-situ Stress (Multiple Seam Stress plus Overburden Stress) are shown in Figures 10 and 11.

Following the assumption that the seven pillars remaining in the Eagle seam have shed their load entirely and resulted in a different

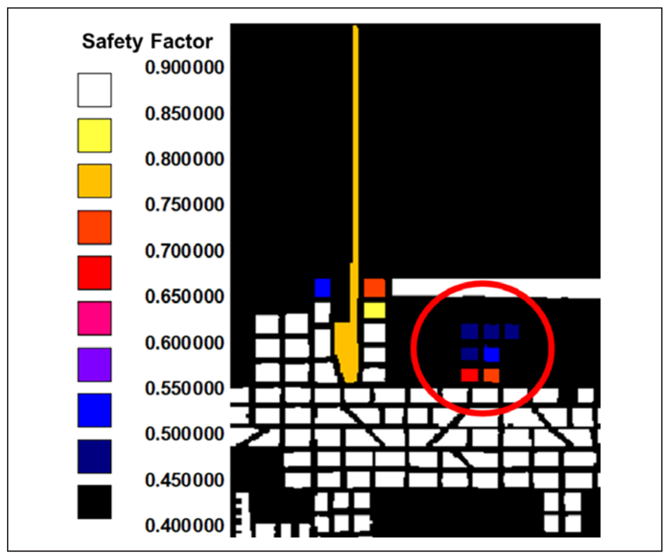

Figure 9. Pillar stress safety factors for the underlying Eagle seam after retreat mining the preceding panel

gob shape, and therefore calibrated modulus, the decision was made to split up the barrier between those two adjacent gobs and assess the stability of that barrier to determine what load-carrying capacity remained (See Figure 12). Additionally, failed pillars to the north are also depicted.

Based on the above barrier analysis, it is apparent that at least a portion of that barrier has failed and most likely at least half of it has. Moreover, a portion of the barrier was also under more stress and likely "damaged" by the front abutment wave during retreat of the preceding panel in the active seam.

At this point, it was decided that the majority of that barrier separating gobs in the Eagle seam had likely failed, shedding load, and

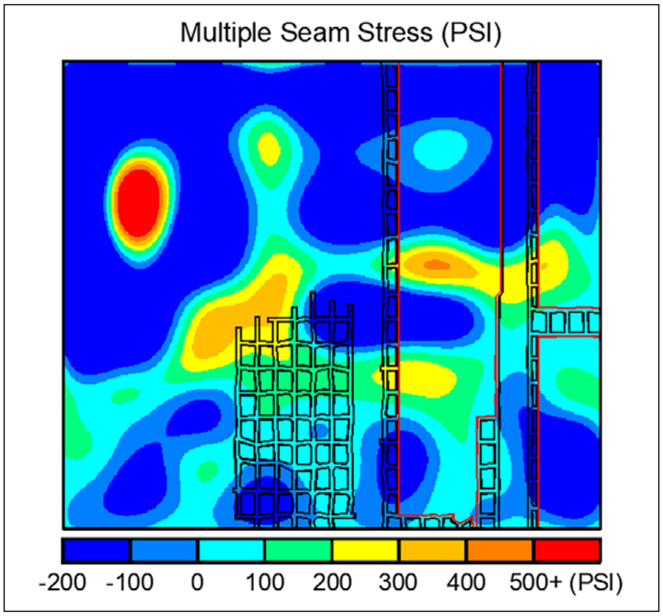

Figure 10. Plot of the Multiple Seam Stress calculated by LaModel and overlain on the active seam workings after retreat mining the preceding panel

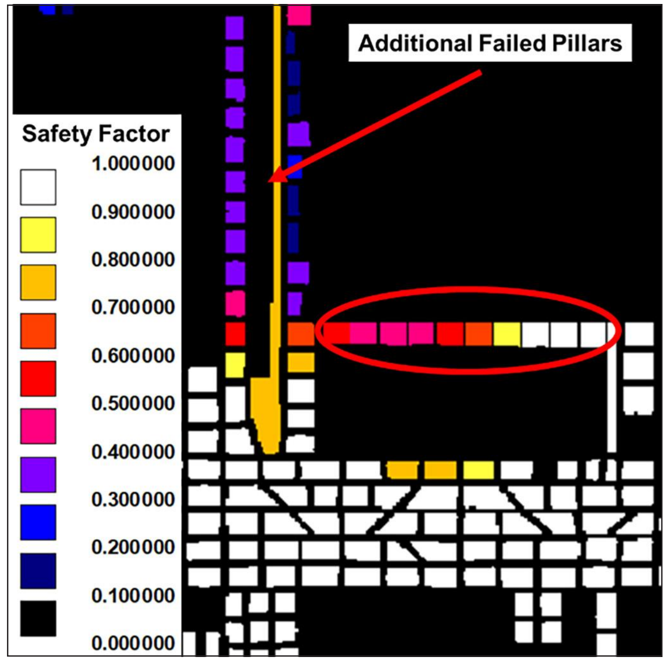

Figure 12. Pillar stress safety factors for the Eagle Seam barrier circled in red after retreat mining the preceding panel

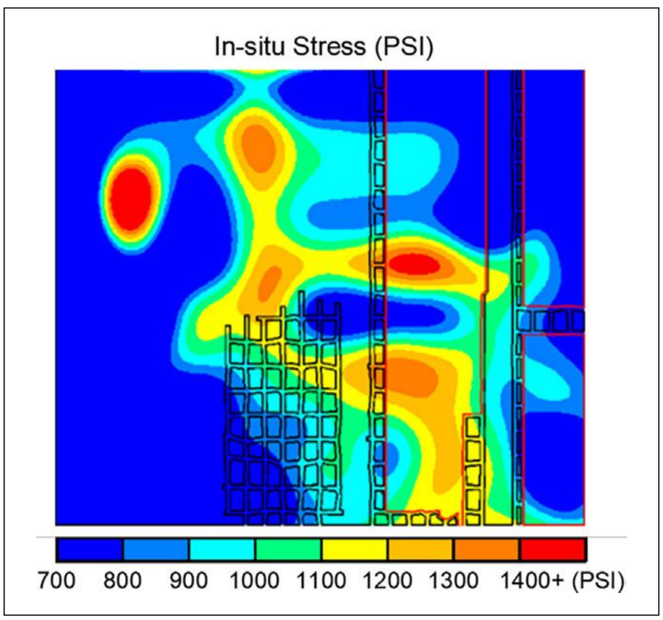

Figure 11. Plot of the In-situ Stress calculated by LaModel and overlain on the active seam workings after retreat mining the preceding panel

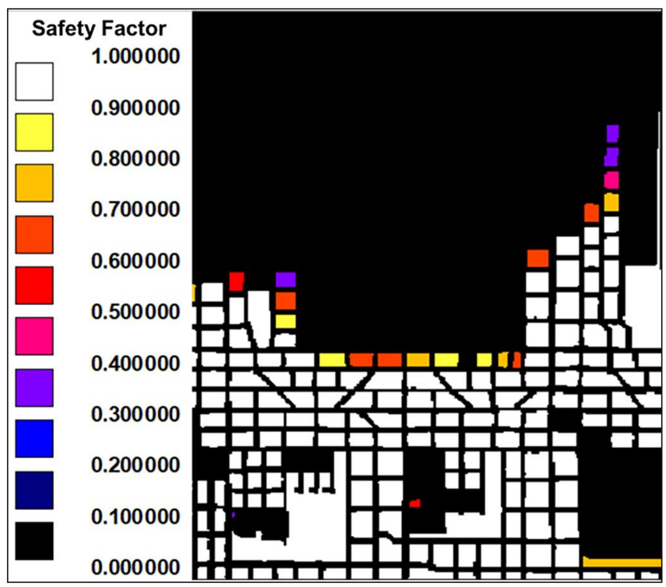

Figure 13. Eagle seam gob extent after retreat mining the preceding panel in the active seam and considering pillar yielding.

that the remaining pillars shown to the north had also failed resulting in a more widespread gob area than was originally thought and that the response from the Eagle seam undermining actually looked more like what can be seen in Figure 13.

Again, plots of the Multiple Seam Stress and the In-situ Stress based on this change to the model and assuming that this wide, deep gob modulus remained unchanged, are shown in Figures 14 and 15 and can be compared to Figures 10 and 11.

Comparing Figures 14 and 15 to Figures 10 and 11, several observations can be made. First, we see a significant change in the multiple seam stress calculated by LaModel. Not only has the geometrical distribution changed, but so has the magnitude. The magnitude of the maximum multiple seam stress over the area of interest in the study panel has increased from about 330 psi. to about 460 psi., an increase of about 40%. This is significant, and when added to the existing overburden stress results in an in-situ stress plot that is much closer to matching the conditions observed

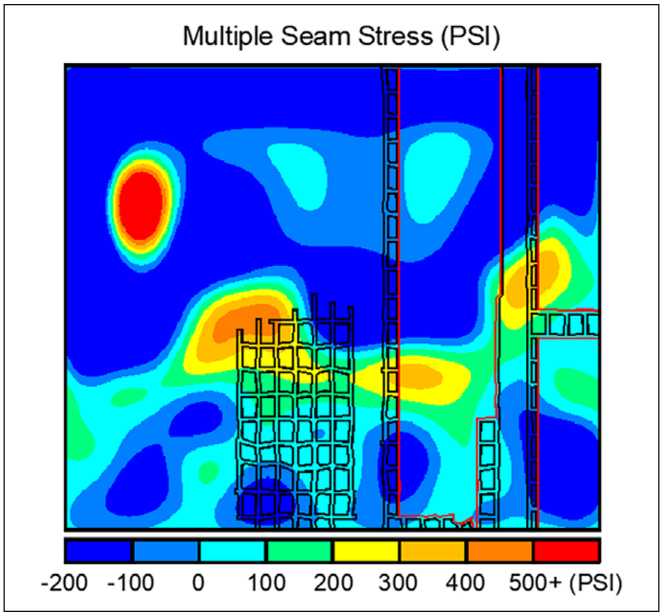

Figure 14. Plot of the Multiple Seam Stress calculated by LaModel and overlain on the active seam workings after Eagle seam gob modification based on pillar stability analysis

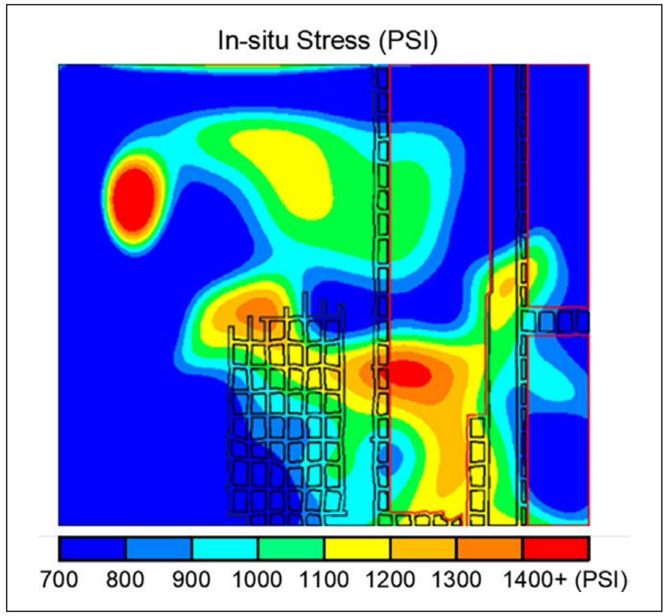

Figure 15. Plot of the In-situ Stress calculated by LaModel and overlain on the active seam workings after Eagle seam gob modification based on pillar stability analysis

in the field. The highest in-situ stress levels, in this panel, now occur where the 3-Left crosscut was unable to be completed, and even more significant destressing is observed in the #5 entry.

PILLAR STABILITY ANALYSIS

Once the theory of a potential active subsidence event and the path-dependent calibration of the LaModel program was complete, the resultant impact on the 2 Gas seam pillar stability was then analyzed. The Pillar Stress Safety Factors for the study panel were calculated based on the original 9-ft. mining height, the average for the area of interest (See Figure 16).

From this, it was clear that the Safety Factors of the pillars in this area did not appear to match appropriately with the observed amount of damage to the pillars or the amount of observed floor heave. Also, it was not possible to calculate the safety factors of the pillars where the crosscuts had not been completed. Therefore, additional calibration of the in-situ coal strength and/or the modeled mining height was required. Also, a final step was added to the model so that the pillars that hadn't been successfully completed could be analyzed.

The driving factor behind the magnitude of both the multiple seam stress, and therefore the in-situ stress, is the overburden depth. This implies a physical limit on the total amount of stress the seam will be subjected to during mining and that some additional factors must be coming into play in the study panel. Traditionally, the binder between the upper and lower 2 Gas splits at the study mine has been a reasonably thin shale and can be strong enough to provide significant cutting resistance for the continuous miner. However, in the study panel, this binder is considerably thicker than usual, up to nearly 4 ft. in thickness. Multiple joint sets were observed in the roof of this panel and could, at least conceptually, negatively impact the strength of this parting.

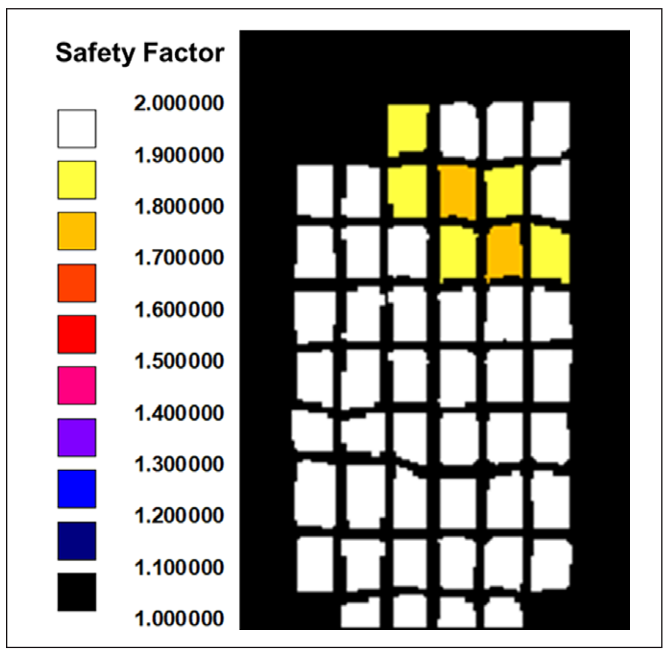

Figure 16. Pillar Stress Safety Factors for the 2 Gas Seam based on a mining height of 9 ft. and a Mark-Bieniawski pillar strength of 900 psi

To account for this, rather than increase the mining height beyond the average in the model, it was decided to decrease the in-situ coal strength in LaModel for the 2 Gas seam from 900 psi to 800 psi, which is just over a 10% reduction in strength. From this, the pillar stress safety factors for the study panel were calculated again based on these changes (see Figure 17).

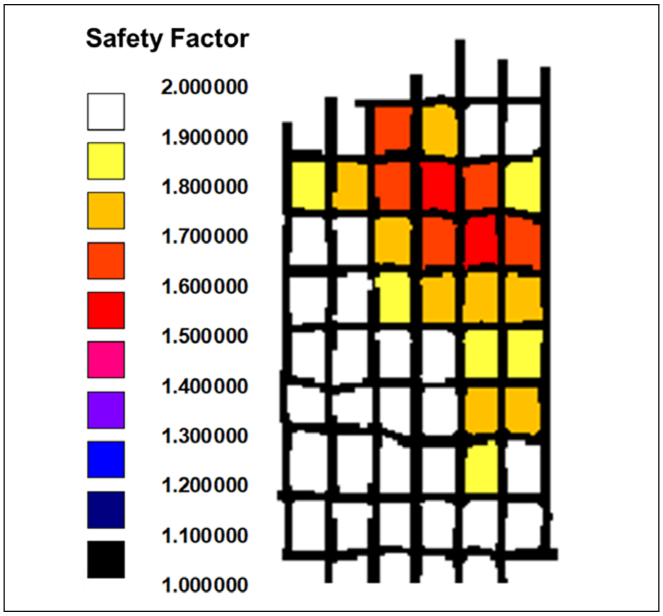

Figure 17. Pillar Stress Safety Factors for the 2 Gas Seam based on a mining height of 9 ft. and a Mark-Bieniawski pillar strength of 800 psi

From this modification and assessing the pillars that had yet to be completed, a much clearer picture of the stability of the pillars in this area was obtained. Even though the individual pillar stress safety factors exceed 1.4 and the stability factors exceed 1.5, this is more likely to be what was observed than what was calculated using an in-situ coal strength of 900 psi. This does not necessarily imply that the pillars in this area were failing, and they did not appear to be at the last opportunity for observation. It simply means that the significant convergence was occurring and that the observed damage to the pillars appeared to be more than what was suggested by safety factors exceeding 1.8.

LIMITATIONS

While this study provides valuable insights into the complexities of multiple-seam mining scenarios using the LaModel program, it is important to acknowledge its limitations. The primary limitation is that our findings are based on a single case history—the analysis of a development panel in the No. 2 Gas seam in Southern West Virginia. While this case offers a detailed and context-specific understanding of the interaction between multiple seams, particularly in path-dependent mining scenarios, it represents only one specific set of geological, mining, and operational conditions.

The uniqueness of each mining scenario, characterized by varying seam properties, mining techniques, and geological conditions, implies that the findings in this paper may not be universally applicable. This study's reliance on a single case history limits the ability to generalize the results to other mining environments with different characteristics. Additionally, the modeling approach used in this study, while robust, inherently contains assumptions and simplifications that may not fully capture the complexities of all real-world mining operations.

This study employed elastic-plastic material models, which are widely accepted by LaModel practitioners who are typically less concerned with the post-yield behavior of coal pillars. These models effectively capture the initial yielding but simplify the post-yield behavior, not accounting for strain softening. Strain softening models can more accurately simulate the progressive failure of coal pillars, providing insights into the gradual reduction in strength and stiffness after the peak stress is reached.

Despite the potential advantages of strain-softening models in certain scenarios, their application in LaModel analyses is less common due to the increased complexity in calibrating and interpreting the results from strain-softening models. Future research exploring strain-softening models might reveal more accurate results and could eliminate the need to look for failed pillars in the model, replace those pillars with gob material, and recalibrate the gob stiffness.

Finally, this study concludes by reducing the in-situ coal strength of the active seam to provide a better understanding of the damage to the pillars that was observed in the study panel. This does not mean that the empirically defined 900 psi in-situ coal strength should be changed for analyzing other scenarios including other locations within the No. 2 Gas seam. Additionally, this means that the final pillar stability analysis of the study panel is not directly comparable to stability factors calculated by ARMPS or ACPS.

Given these limitations, it is crucial to approach the findings of this study with an understanding of its context-bound nature. There is a need for further research in this area, encompassing a broader range of case histories with diverse mining conditions and geological settings. This will enable the development of more generalized models and strategies for multiple-seam mining scenarios. Continued research is essential to enhance the understanding of the interaction between seams in different mining contexts and to improve the practical engineering applications of modeling tools such as LaModel.

CONCLUSIONS

This study's comprehensive analysis using the LaModel program underscores the complexities inherent in modeling path-dependent mining scenarios, particularly in multiple-seam situations. This case study in Southern West Virginia, focusing on the No. 2 Gas seam, highlighted the critical impact of previous mining activities in adjacent seams on current operations. The termination of mining in the study panel due to extensive rib damage and deformation, adjacent to both the Eagle and Williamson seam boundaries, was a pivotal observation.

The findings suggest that the traditional approach of LaModel, treating each mining step as an independent steady-state condition without considering dynamic stress changes, may not always suffice in capturing the intricacies of multiple-seam interactions. Particularly, the increased stresses and resultant convergence in the underlying Eagle seam, exacerbated by retreat mining in the No. 2 Gas seam, were pivotal in understanding the complex stress environment affecting the study panel.

The recalibration of the model, considering the path-dependent nature of the mining sequence and adjusting for the actual conditions encountered, such as the increased mining height and varying coal strength, provided insights that were more aligned with the observed field conditions. This recalibration demonstrated a significant increase in multiple-seam stress, leading to a better understanding of the subsidence and deformation experienced.

This paper's primary contribution lies in highlighting the necessity for ground control engineers to incorporate both historical and future states of stress in their analyses, especially in scenarios involving multiple seams. As such situations become increasingly common, the ability to accurately model these complex interactions becomes crucial. This study reinforces the need for continuous evaluation and adjustment of modeling parameters to reflect the dynamic nature of mining environments, ensuring safer and more effective mining operations.

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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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