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Enhancing Pillar Stability in a Deep-Cover Longwall Mine Using the LaModel Program: A Comparative Analysis

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ABSTRACT

The stability of gateroad pillars is crucial in deep-cover longwall mining, especially during transitions to wider panel layouts. This study evaluates the transition from a 700-foot to a 1,000-foot panel layout with an inter-panel barrier in a deep-cover longwall mine in Southwestern Virginia to identify a configuration that enhances stability and reduces operational risks. Using the LaModel program, three pillar configurations were simulated to assess their performance based on stress distributions and pillar safety factors. These included the previously used 4-Entry Yield-Abutment-Yield layout, the current 3-Entry Yield-Abutment layout with a 220-ft inter-panel barrier, and the proposed 3-Entry Yield-Yield layout with a 320-ft inter-panel barrier. The findings of this study suggest that the proposed 3-Entry Yield-Yield pillar layout is more effective in managing stresses in deep-cover mining environments. By optimizing pillar placement and improving load management, this layout could positively impact mineworker safety and health. The study underscores the importance of advanced simulation tools in developing innovative solutions to address the challenges of modern longwall mining operations.

INTRODUCTION

The stability of underground mine workings is crucial in deep-cover longwall coal mining, particularly in regions such as Southwestern Virginia, where mining depths often exceed 2,000 ft. Ensuring gateroad pillar stability is vital to maintaining safe mining operations in these environments. During the transition from a 700-foot panel layout to a 1,000-foot layout with an inter-panel barrier in the Pocahontas #3 seam, new ground control challenges in managing stress emerged, primarily in excessive floor heave.

Advancements in computational modeling, mainly using LaModel (Heasley, 1998), enable more detailed simulations of stress distributions and deformations under such demanding conditions. This study leverages LaModel to compare the performance of three gateroad pillar layouts used or proposed in this mine. The objective is to identify design improvements that enhance stability and mitigate adverse ground control conditions, such as floor heave, particularly under wider panel configurations.

This research focuses on the analysis of stress redistributions and pillar safety factors across the three pillar layouts: the previous 4-Entry Yield-Abutment-Yield (Y-A-Y) layout, the current 3-Entry Yield-Abutment (Y-A) layout with an inter-panel barrier, and a proposed 3-Entry Yield-Yield (Y-Y) layout (Mark and Barton, 1988; Barron et al., 1994) with an inter-panel barrier. The insights derived from these analyses are expected to offer valuable insight for optimizing gateroad design and improving ground stability in longwall mining operations under deep cover.

MINE LAYOUT

Taking a closer look at the three pillar layouts, the first layout, successfully used for several years, is a 4-Entry system with a Y-A-Y pillar arrangement and a panel width of 705 ft. The pillars in this configuration comprise 175-ft by 450-ft abutment pillars and 50-ft by 150-ft yield pillars (C-C), effectively managing stress concentrations in the gateroad (see Figure 1).

The current layout incorporates a 3-Entry system with a 220-ft (C-C) inter-panel barrier and was introduced to accommodate a 1,000-foot-wide panel. This design employs a Y-A pillar system with 90-ft by 160-ft abutment pillars and 60-ft by 160-ft yield pillars (C-C) (see Figure 2).

However, challenges have arisen with this layout, particularly concerning floor heave observed in the tailgate entries on the far side of the barrier. These issues prompted a reevaluation of the design to find alternative solutions

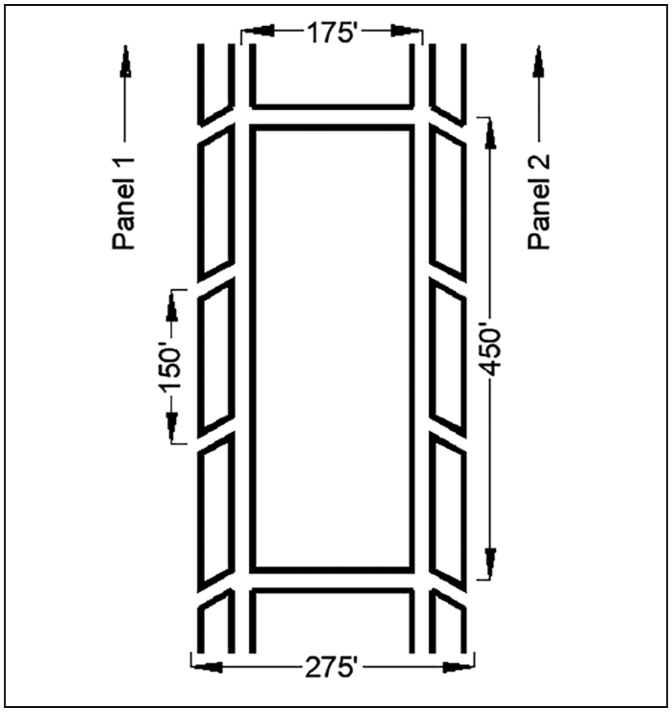

Figure 1. Plan view of mine map depicting the previously used four-entry yield-abutment-yield pillar layout

to mitigate stress concentration and maintain gateroad stability.

In response to these challenges, a proposed 3-Entry layout introduces a Y-Y pillar arrangement with a wider 320-ft (C-C) inter-panel barrier with 50 ft by 160 ft (C-C) yield pillars (see Figure 3).

This new design aims to improve stability by distributing stress more evenly across the barrier pillar, thereby reducing loading conditions that contribute to floor instability in the current layout. This proposed design is expected to reduce floor heave in the 1,000-ft panel configuration by optimizing pillar placement and function.

METHODOLOGY

This study evaluates the stress distributions and pillar performance under two critical scenarios: first, the stress profiles measured across the gateroad following the completion of the first panel, and second, the stress profiles observed across the pillars isolated between two gobs after mining the second panel. Additionally, the analysis includes evaluating pillar safety factors to better understand the pillars' stability under varying stress conditions. By comparing these two critical stress environments, this study aims to identify stress redistribution patterns and assess the pillar layouts' effectiveness in maintaining gateroad stability.

The primary tool used for this analysis is the LaModel program, which allows for a detailed examination of stress profiles and safety factors under different pillar layouts. Each pillar configuration is evaluated regarding stress distribution and pillar safety. The insights gained from this evaluation are intended to inform future improvements to pillar design in deep-cover longwall mining operations.

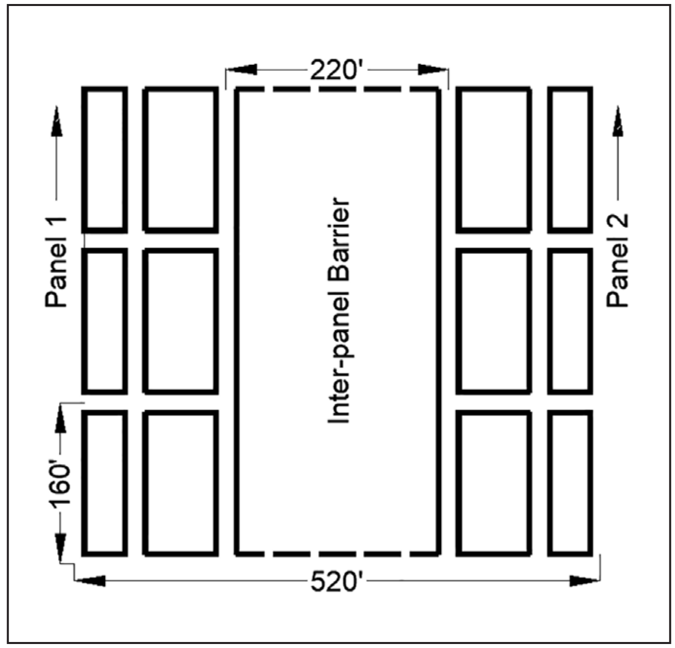

Figure 2. Plan view of mine map depicting the currently used three-entry yield-abutment pillar layout with an inter-panel barrier

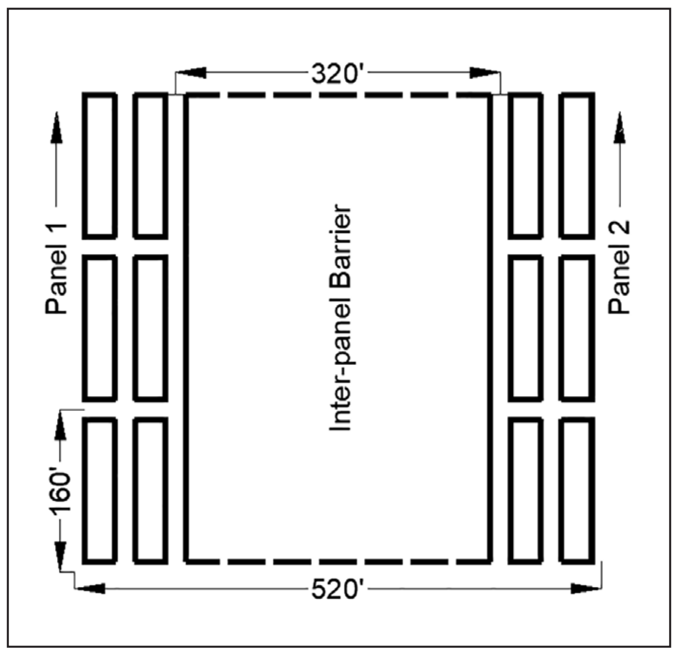

Figure 3. Plan view of mine map depicting the proposed three-entry yield-yield pillar layout with wider inter-panel barrier

LAMODEL

The LaModel 3.0 program was selected to simulate the pillar behavior in this study due to its compatibility with widely used calibration procedures, such as those in the Analysis of Coal Pillar Stability (ACPS) program (Mark and Agioutantis, 2018). Using LAMPRE 3.0, LaModel's preprocessor, the coal seam was discretized into 10-ft elements. A grid size of 1,000 × 1,000 elements (or 10,000 × 10,000 feet) was selected to create a sufficient buffer and minimize potential edge effects. Openings were modeled at a nominal 20 ft. even though the combined belt/track entries are 22 ft. wide as mined. Symmetric boundary conditions were applied on all sides, and the overburden was modeled as a flat 2,000 ft. for consistency between the layout comparisons.

CALIBRATION OF THE MODEL

Accurate calibration of input parameters is critical to achieving reliable output in numerical models like LaModel. Calibration requires using the most reliable data sources, whether derived from measurements, observations, or empirical data. This analysis calibrated three parameters: rock mass stiffness, gob stiffness, and coal strength. These were calibrated in sequence, as each subsequent parameter's calibrated value depended on the previous one (Heasley, 2008).

In LaModel, the stiffness of the rock mass is determined by the rock mass modulus and lamination thickness (see Figure 4).

Adjusting these parameters alters the stiffness of the overburden, which in turn affects the extent of the abutment. For this study, the rock mass modulus was held constant at 3,000,000 psi. Lamination thickness was adjusted to reflect the empirically suggested abutment extent, where 90% of the load is distributed within a distance of five times the square root of the depth (H) (Mark, 2010).

The final gob modulus, which defines the stiffness of the strain-hardening gob material, controls the magnitude of the abutment load. This was conceptualized using the abutment angle (see Figure 5). Based on stress measurements from five U.S. mines, an average abutment angle of 21° was used (Mark, 1992). To match this angle, gob modulus values of 300,000 psi and 180,000 psi were used for the 705-ft and 1,000-ft panel layouts, respectively.

The Mark-Bieniawski pillar strength was used to calibrate coal strength, assuming an in-situ coal strength of 900 psi and a mining height of 7.5 ft. To match the Mark-Bieniawski pillar strength, an elastic-plastic material model was chosen for the coal. This material model was preferred due to its widespread understanding and ability to match pillar strength without further calibration of in-situ coal

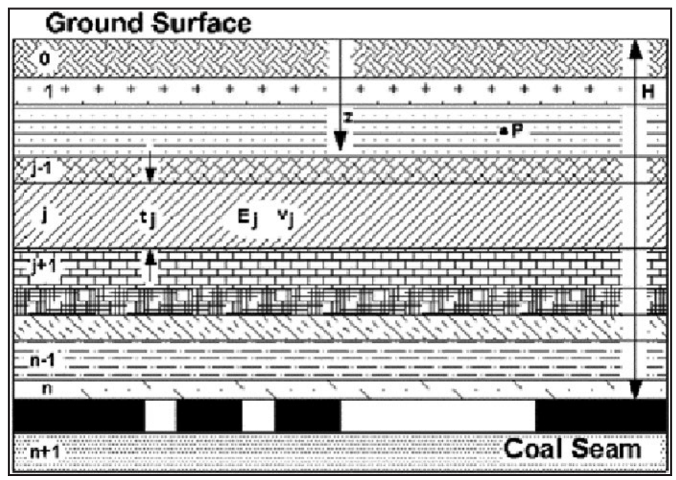

Figure 4. Overburden layers indicating thickness, modulus, and Poisson's ratio

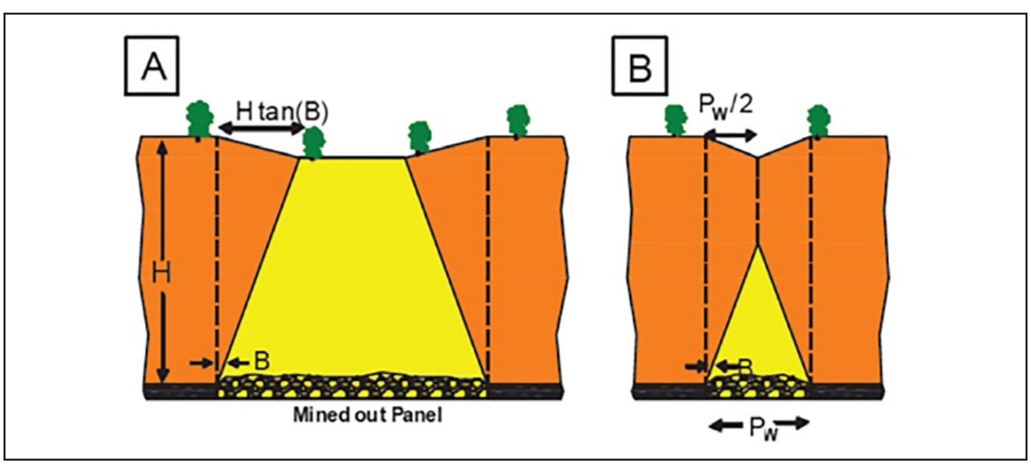

Figure 5. Conceptualization of the abutment angle depicting a supercritical panel (A) and a subcritical panel (B) (after Mark, 2010)

strength, which would be influenced by pillar size in strain-softening materials.

STRESS ANALYSIS

The chart below illustrates the vertical stress profiles across the gateroads after completing the first-panel mining. This analysis compares three gateroad pillar configurations: the previously implemented 4-Entry layout, the current 3-Entry Y-A configuration, and the proposed 3-Entry Y-Y layout (see Figure 6).

The stress profiles capture the total vertical stress experienced at each element across the gateroads. As expected, the vertical stresses are the highest closer to the gob edge. The proposed 3-Entry Y-Y layout, for example, shows the highest peak stress adjacent to the gob of the active panel. However, this stress dissipates across the large barrier resulting in reduced stress levels as the unmined adjacent panel is approached compared to the 4-Entry and 3-Entry Y-A layouts. This reduction is most notable in the tailgate region of the subsequent panel, where managing ground stability is critical. These findings suggest that the 3-Entry Y-Y layout has the potential to redistribute stress more effectively, reducing concentrations and improving overall stability within the gateroad.

Analyzing the barrier pillar stability for the 4-Entry, 3-Entry Y-A, and 3-Entry Y-Y configurations, the stress distribution across the abutment/barrier pillar was closely compared. The 4-Entry scenario had the highest average stress of 5,988 psi. The 3-Entry Y-A scenario showed an average stress of 5,110 psi, while the 3-Entry Y-Y scenario demonstrated the lowest average stress of 4,878 psi. The 3-Entry Y-Y scenario provides approximately a 19% reduction in the average stress compared to the 4-Entry scenario and a 5% reduction in the average stress compared to the 3-Entry Y-A scenario. The reduction is particularly notable near the adjacent tailgate entries on the far side of the barrier, where the 3-Entry Y-Y configuration is intended to redistribute stress more evenly across the pillars. In the #3 entry, adjacent to the barrier, a stress reduction of approximately 17% was observed compared to the 4-Entry scenario and 11% for the 3-Entry Y-A scenario. This indicates the potential for the Y-Y layout to improve stability and mitigate stress-induced floor instability.

Building on the findings from the initial analysis of the first-panel mining, further investigation was conducted to assess the stress profiles across the barrier or abutment pillar in the 4-Entry scenario, isolated between gobs after the second-panel mining. This detailed examination clarifies the maximum loading conditions these pillars are expected to resist (see Figure 7).

Based on the LaModel simulation, the average stress values for the 4-Entry, 3-Entry Y-A, and 3-Entry Y-Y scenarios were 9,038 psi, 7,640 psi, and 7,050 psi, respectively.

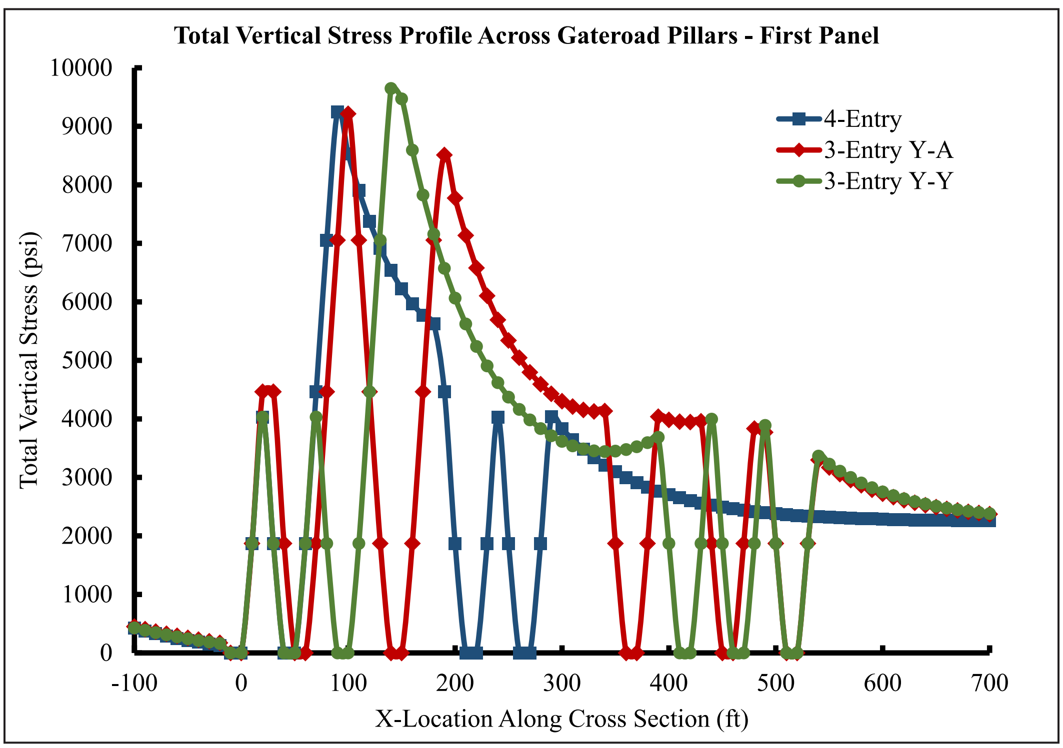

Figure 6. Stress profiles across the gateroad pillars after first-panel mining for the three scenarios

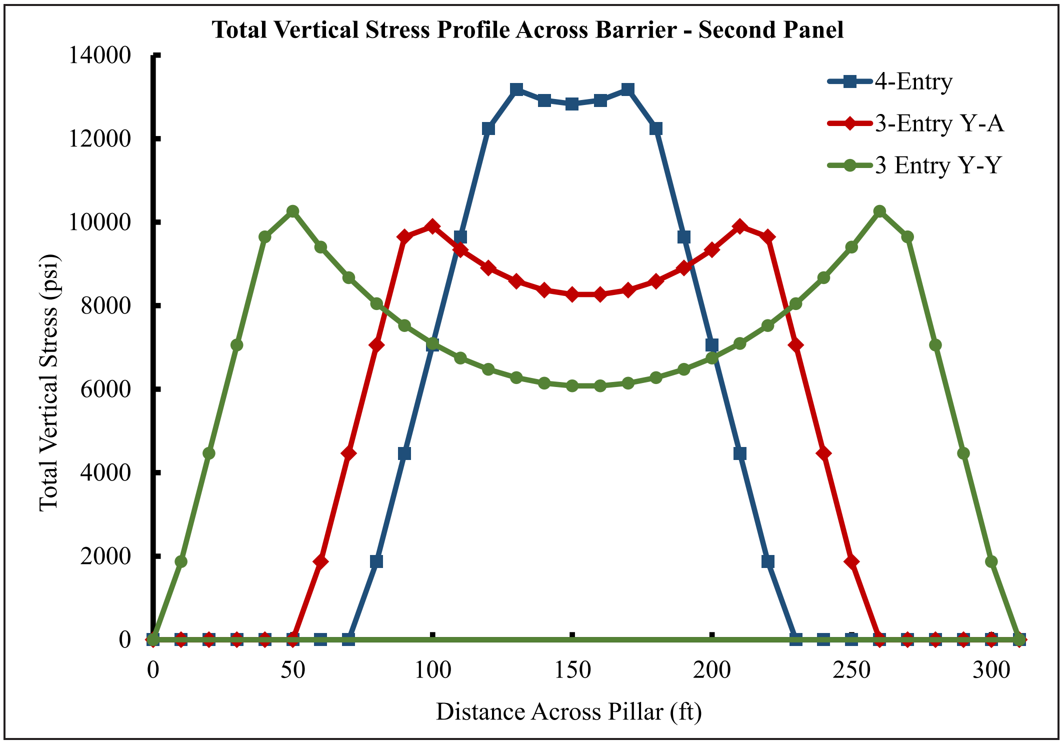

Figure 7. Isolated stress profile across the barrier pillars after second-panel mining for the three scenarios

The analysis highlights the significant stress reductions in the 3-Entry Y-Y scenario compared to the other designs. Specifically, there is a 22% reduction in average stress compared to the 4-Entry scenario and an 8% reduction compared to the 3-Entry Y-A layout. These findings demonstrate the potential of the 3-Entry Y-Y configuration to enhance stability by reducing stress concentrations in critical areas.

STABILITY ANALYSIS

In this section, the focus shifts to evaluating the stability of the gateroad pillars under the different layout configurations to assess their ability to manage underground stresses and maintain structural integrity. The analysis compares the safety factors for three primary scenarios: the 4-Entry layout, the 3-Entry Y-A layout, and the 3-Entry Y-Y layout (see Figure 8).

The safety factor analysis reveals notable differences in pillar stability across the three configurations. After calculating the weighted average safety factors based on pillar widths, the results indicate that the 4-Entry configuration has an average safety factor of 1.3. The 3-Entry Y-A configuration shows a slightly higher safety factor of 1.5, while the 3-Entry Y-Y configuration significantly outperforms both, with a weighted average safety factor of 2.3. These findings underscore the potential of the 3-Entry Y-Y layout to provide enhanced stability, particularly when considering pillar widths and the layout's capacity to distribute stress more effectively.

Under isolated loading conditions following the second-panel mining, the barrier pillar safety factors analysis revealed essential variations between the three configurations. The 4-Entry layout displayed the lowest safety factor at 1.1, indicating that it operates closer to its stability threshold. In contrast, the 3-Entry Y-A layout demonstrated a more robust safety factor of 1.6, suggesting an improved capacity to manage the stresses induced by second-panel mining. The 3-Entry Y-Y layout showed the highest safety factor at 2.2, offering superior stability under these conditions. These results highlight the ability of the 3-Entry Y-Y layout to distribute stress better, thus maintaining structural integrity. The significant increase in safety factor for the 3-Entry Y-Y layout further reinforces its potential increased effectiveness in mitigating risks associated with mining-induced seismicity under isolated loading conditions.

CONCLUSIONS

This comparative analysis of gateroad pillar stability in a deep-cover longwall mine using the LaModel program provides critical insights into the performance of three distinct pillar configurations under varying stress conditions. The results demonstrate reduced stress concentrations and

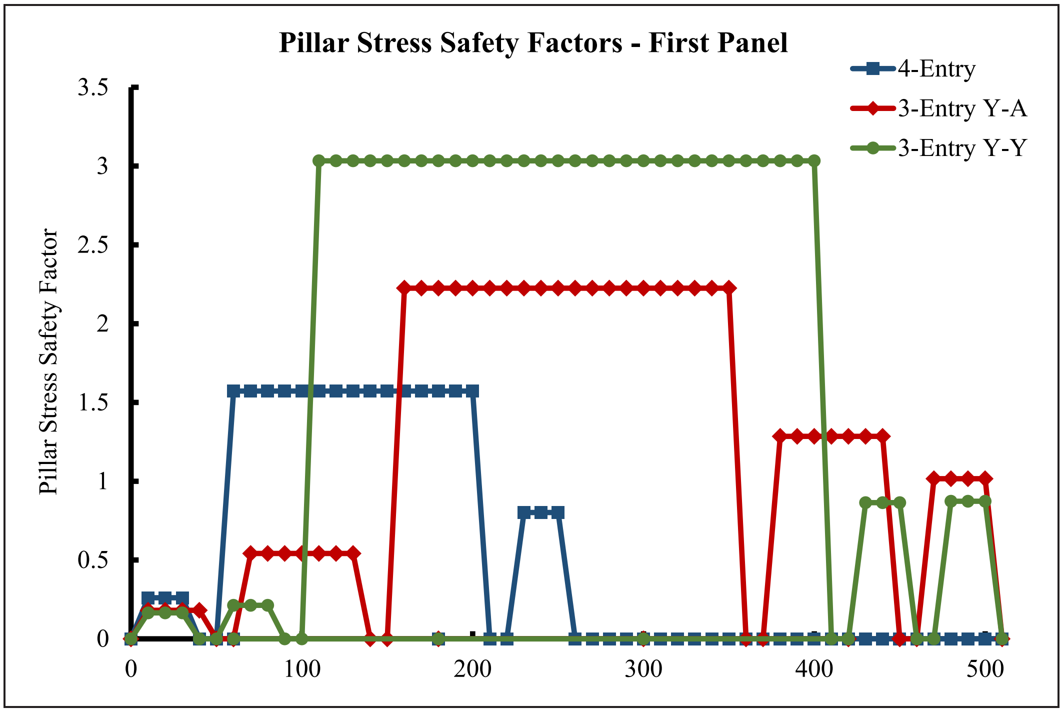

Figure 8. Safety factors of the gateroad pillars after first-panel mining for the three scenarios

improved pillar stability by transitioning from the traditional 4-Entry layout to the proposed 3-Entry Y-Y layout.

In both the first and second-panel mining scenarios, the 3-Entry Y-Y layout consistently outperformed the other designs, reducing stress. After first panel mining, the 3-Entry Y-Y configuration achieved a 19% reduction in the average stress across the 4-Entry abutment pillar and a 5% reduction in the average stress across the barrier compared to the 3-Entry Y-A layout, with notable improvements observed on the far side of the barrier in the subsequent tailgate where floor instability was observed. Similarly, after second-panel mining, the 3-Entry Y-Y layout exhibited a 22% reduction in stress across the abutment/barrier pillar compared to the 4-Entry configuration and an 8% reduction compared to the 3-Entry Y-A layout. These reductions indicate that the 3-Entry Y-Y design provides a more balanced and efficient load distribution, potentially decreasing the risks of mining-induced seismicity.

The safety factor analysis of the barrier/abutment pillar is most critical considering isolated loading conditions following second-panel mining. In this scenario, the 3-Entry Y-Y configuration achieved a barrier pillar safety factor of 2.2, compared to the 4-Entry layout and the 3-Entry Y-A layout with safety factors of 1.1 and 1.6, respectively. This substantial increase in safety factor indicates the 3-Entry Y-Y layout's superior ability to maintain pillar integrity under the most demanding conditions, ensuring greater long-term stability. These findings underscore the potential of the 3-Entry Y-Y design to help mitigate the risks associated with mining-induced seismicity, offering a potential solution for maintaining structural integrity in wider panel configurations and deeper cover environments.

LIMITATIONS AND FUTURE RESEARCH

While this study provides valuable insights into gateroad pillar stability under deep-cover mining conditions, it is essential to acknowledge certain limitations. First, the analysis is based on a single case history from a specific longwall mine in Southwestern Virginia. As a result, the findings, while indicative, may not be representative of all mining operations or geological settings. Variations in geological conditions, overburden properties, and mining depths can significantly affect the performance of gateroad pillar layouts, and further studies are necessary to validate these results across a wider range of mines and conditions.

Despite some identified challenges, the previous 4-Entry yield-abutment-yield design was largely successful in maintaining stability over many years of operation. The issues observed in the current 3-Entry Y-A layout, such as floor heave, may not be solely attributed to the pillar design but could also be influenced by factors such as panel width and evolving geological conditions. When interpreting the results, this context should be considered, particularly when recommending future pillar design modifications.

Future research should expand this analysis' scope to include different mines with varying geological conditions and mining depths. Advanced numerical modeling incorporating a broader range of variables—such as dynamic loading conditions, multi-seam interactions, and more detailed material properties—would further improve our understanding of pillar behavior. Additionally, real-time in-field monitoring of stress and deformation during longwall mining could provide valuable data to refine and validate computational models like LaModel.

Finally, while the 3-Entry Y-Y layout shows promise in reducing stress concentrations and improving pillar stability, continuous monitoring and performance assessment will ensure its long-term success. Future research should also explore potential optimizations to this design, particularly concerning inter-panel barrier dimensions and pillar yield properties, to further enhance its effectiveness in managing underground stresses.

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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