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Evaluation of Alternative Chain Pillar Designs in a Deep Longwall Mine

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ABSTRACT

Design of chain pillars in a longwall mine setting is one of the main engineering controls on the global and local stability of the mine. Challenges with roof instabilities, floor heaves, and pillar failures can be alleviated, to some extent, by careful design of gateroad configurations and chain pillars. This work investigates three different alternative designs in a three-entry-system gateroad configuration with an inter-panel barrier in a longwall mine in Virginia. Starting with the current design, which has faced challenges such as excessive floor heave, a geomechanical model developed in 3DEC software is validated by monitoring in-situ pillar stress in the yield, abutment, and barrier pillars in the mine. Next, three different chain pillar designs are evaluated in the model with a focus on roof sagging, floor heave, and pillar average stress. Results show the relationships among the alternative designs and instabilities associated with roof, pillar, and floor in the study mine, providing insights for optimizing longwall mining designs in deep-cover settings.

INTRODUCTION

Deep longwall mining under mountainous terrain introduces unique ground control challenges that might not be present in shallower operations. These challenges include induced seismicity in the pillar, roof or floor, gateroad closure due to roof sag or floor heave, and rib instabilities. Pillar sizing and mine layout design are known engineering factors that can potentially mitigate geology-driven instabilities. However, geology variation along and across longwall panels make it difficult to come up with a single design for a district or entire mine. In other words, a mine layout design needs to accommodate a range of possible geology variations in the intended area. For example, floor geology might change along a panel, so one layout that works for the area with a strong sandy shale floor might lead to operationally problematic floor heave where floor is weak fireclay. Thus, alternative mine designs need to be evaluated for a range of mine geology with respect to potential challenges such as roof sag, floor heave, and induced seismicity. However, the question is what tools and methodologies are necessary for finding an optimum design that minimizes geology-controlled ground instability. The current practice in the mining industry is to follow previous experiences, but in the case that a new design is being tested with little to no historic data and experience, new tools are needed for evaluation purposes.

NIOSH has initiated a research project in a deep longwall mine in Virginia where a new mine area is being developed with a 1,000-ft, single-panel district design and 220-ft barrier pillars isolating each panel. The previous mine areas had a 6-panel district design with 700-ft-wide panels but had challenges with respect to ventilation and induced seismicity (Khademian et al., 2024). Thus, the new layout was intended to improve upon the previous designs as each panel can be sealed right after longwall recovery, benefiting ventilation efficiency and potential seismicity in the mined-out panels. Extensive instrumentation was conducted to monitor pillar pressure and roof and floor deformations during the first panel mining.

Mining the first panel proved this design efficient; however, some challenges arose when approaching areas with a weak fireclay floor. During mining of the first panel, an area with weak fireclay floor (low load-bearing capacity floor) showed extensive floor heave slowing the operation. Also, the pillar pressure monitoring showed that the abutment load from the first panel bridged across the barrier pillar (220ft wide) increasing the pillar pressure in the tailgate of the second panel by about 2,000 psi with signs of floor heave and rib damage.

In this part of the research, the pillar and floor instrumentation results were used to initially analyze design performance. Geomechanical models were then developed to evaluate alternative designs that can remedy the current challenges. The evaluation is based on pillar pressure and floor heave in the alternative designs, but it is planned to evaluate the designs with respect to the induced seismicity potential.

DESCRIPTION OF MINE SITE

The longwall mine discussed in this paper operates within the Pocahontas #3 coal seam in western Virginia. This seam is part of the Pocahontas formation, which consists of a thick lens of sediments such as sandstone, siltstone, shale, coal, and claystone (Englund & Briggs, 1974). Located in the Virginia overthrust belt, the mine is near the Keen Mountain fault, a strike-slip fault with compressional overthrusting (Molinda, 2003). Despite some small synthetic thrust faults within the mining area (with a minor offset of up to 5 ft (1.5 m)), the Keen Mountain fault does not seem to affect the mine. The overall mine roof lithology features a sequence of shales varying from 0 to 25 ft (7.6 m) in thickness directly above the Pocahontas #3 coal seam (Figure 1).

Above this shale lies the first sandstone unit, known as Sandstone #1 (SS1), which ranges from 0 to 35 ft (10.7) meters in thickness and is characterized by thin to medium bedding with shale or mica streaks. Above the SS1 unit lies a shale parting, typically ranging from 0 to 5 ft (1.5 m) in thickness, followed by another sandstone unit, SS2. While the shale parting is present in most of the mining area, it is absent in some regions, resulting in one large sandstone unit. The SS2 unit is generally thicker, cleaner, and more massive compared to SS1, with thick to massive bedding. The thickness of the SS2 unit usually varies between 30 ft (9.1 m) and 75 ft (22.8 m).

The geomechanical properties used in the model are listed in Table 1 where E is Young's modulus or deformability modulus, ʋ is Poisson ratio, C is cohesion, F is friction angle, and T is tensile strength of rock. A Mohr-Coulomb strain-softening constitutive law was used for defining inelastic response of rock to stress. To this end, cohesion of the rock was reduced to 6% of its initial values after 0.003 strain.

The friction angles were kept constant. The rock tensile strength was reduced to zero after 0.003 strain. The choice

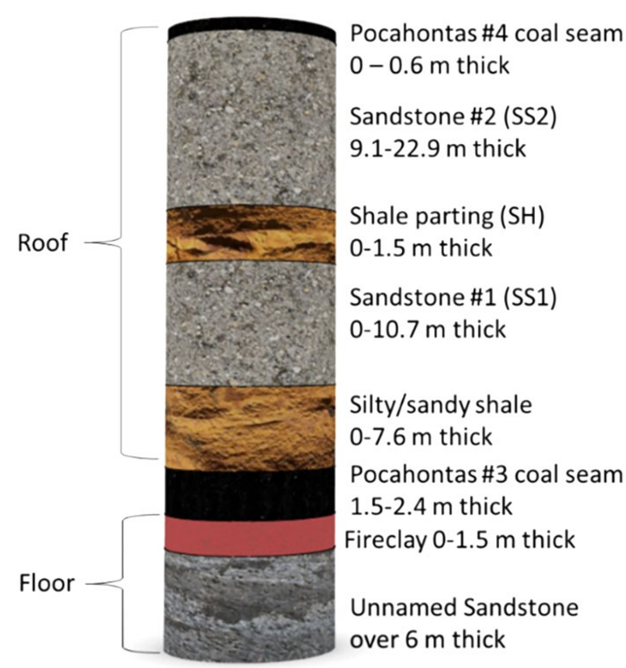

Figure 1. Generalized stratigraphic column of the mine area

Table 1. Geomechanical properties used in the 3DEC model

Rock Type	E (GPa)	ʋ	C (MPa)	F (degree)	T (MPa)
Coal	1.7	0.3	2.0	31	0.7
Dark shale	5.8	0.2	15.2	32.8	7.0
Hard Sandstone	28.4	0.1	23.5	43.9	9.2
Shaly Sand	21	0.1	18.8	38.3	7.9
Sandy Shale	16	0.2	19.1	32.8	7.0
Shale	10.3	0.1	18.8	38.3	7.9
Sandstone	28	0.1	19.6	43.9	9.2
Fireclay	4.3	0.3	8.7	27.7	0.7

of a strain-softening constitutive law is for the purpose of future work where different designs will be evaluated based on their seismic hazard maps.

INSTRUMENTATION SITES

In total, six instrumentation sites were selected for monitoring stress and deformation during the first panel mineby, including two sites on the first panel headgate, two sites on the second panel tailgate, and two sites on the third panel tailgate. In this paper, the focus is on two sites: site #2 which is in the headgate of the first panel (panel 1) and site #4 in the tailgate of the second panel (panel 2) as shown in Figure 2. Overburden depth at these two sites is 1920 ft (584 m). Borehole pressure cells (BPC) were used for monitoring pillar pressure. A BPC is crafted from two steel plates welded along their edges and casted in concrete in a cylindrical form. The gap between the two plates is filled with hydraulic fluid, pressurizing the borehole. Stainless steel tubing connects the BPC to a pressure gauge and pressure transducer outside the borehole (Minoski et al., 2024). To install BPCs, 2-¼-inch (57 mm) boreholes were drilled into pillar ribs to the center of the pillar if not deeper than

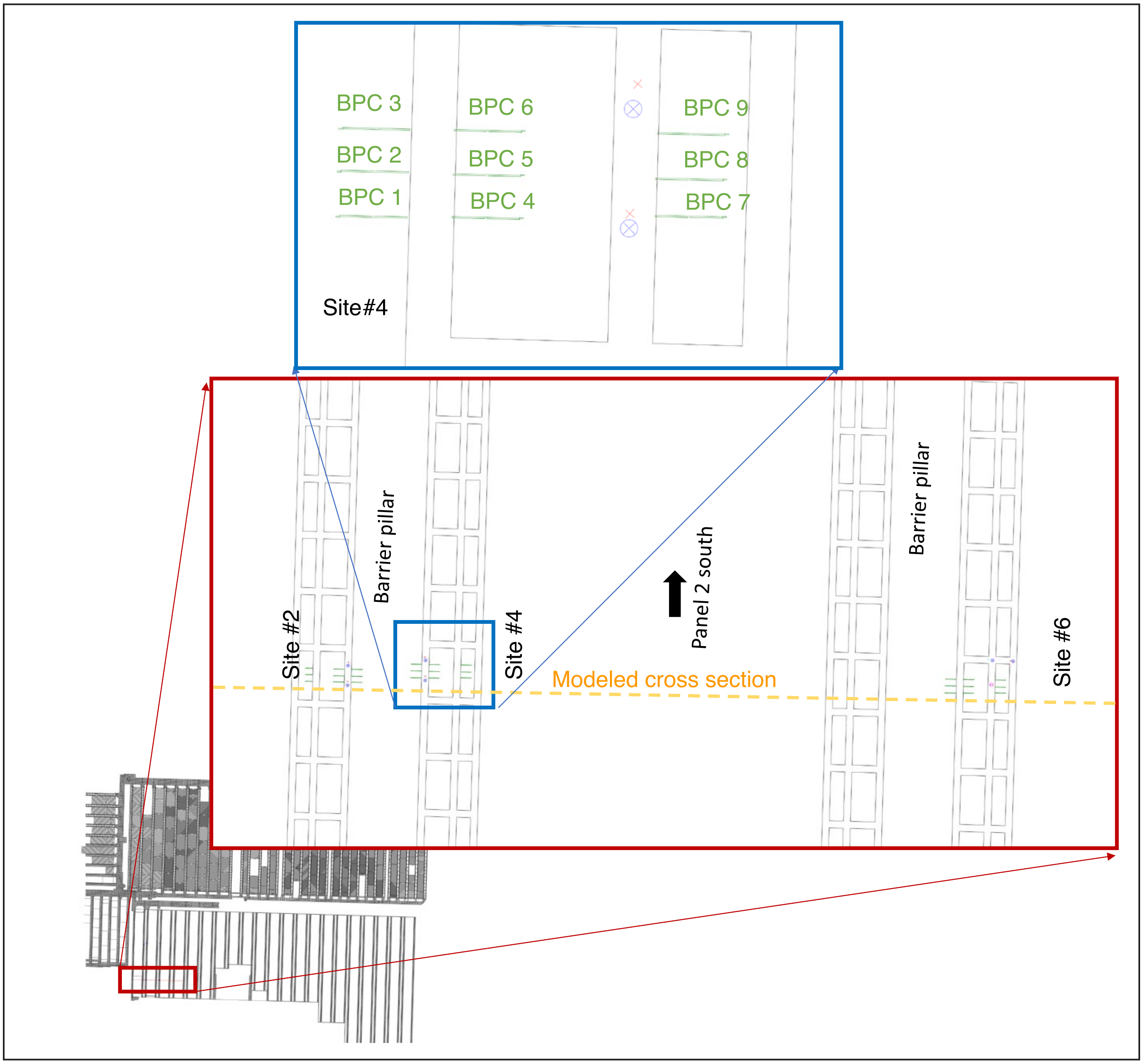

Figure 2. Mine layout, instrumentation sites, and modeled cross section

30 ft (9.1 m). Figure 3 (top) shows drilling for the BPC installation using a double-boom bolter in the study mine. Figure 3 (bottom) shows the insertion of a BPC cell into the borehole.

LiDAR scanning was performed in Panel 1 HG Entry #2 during gateroad development in November of 2023 (Figure 4) and after the first panel mineby in March of 2024. LiDAR scanning was completed using the Maptek I-Site 8200 stationary scanner. Individual scans were taken in succession along the entries, approximately 20 feet apart. Each scan contained between 2.0 to 5.0 million points. Scans collected during the November 2023 site visit were registered together to create a single point cloud. The process was repeated for scans taken during the March 2024 scans. The two-point clouds represent the dimensions of Panel 1 HG Entry #2 before and after development. Surfaces were then created and analyzed using the Maptek PointStudio program. The dimensions of the March 2024 surface were compared to the November 2023 surface, providing changes over time in Entry 2H. The change detection results captured the roof, floor, and rib deformation induced by the passing longwall panel.

Figure 3. Drilling two 30-ft boreholes by a double-boom bolter (top) and installing BPCs with initial pressure set to 1,800 psi (bottom)

Figure 4. Monitoring entry deformation by LiDAR scanner before and after mineby

METHODOLOGY

The objective is to find the mine layout that reduces load transfer to the future panels and also minimize floor heave when weak floor is encountered. The pillars in the current design are 60-ft and 90-ft wide with a 220-ft wide barrier center to center. We used the pillar instrumentation to validate a geomechanical model of the current layout and then used the models to study alternative layouts. Two alternative layouts were studied. One yield-yield-barrier (YYB) with dimensions 50-150-120 ft and another one yield-stable-barrier (YSB) with dimensions 50-50-320 ft. The idea behind the first alternative layout was to further widen the barrier pillar and thus avoid load transfer to the next panel. This design was studied in detail as part of a field evaluation of a yield pillar system at a Kentucky longwall mine by Mark and Barton (1988). The second alternative layout was intended to make the stable pillar wider and thus stiffer so the high pillar pressure in the stable pillar would break the roof strata and thus avoid load transfer to the barrier and the second panel.

GEOMECHANICAL MODEL

A pseudo 2D model at the location shown in Figure 1 was constructed in 3DEC. The model lithology was taken from drilling logs at the closest corehole to the area of interest. Figure 5 shows the model that contains four longwall panels with the current layout of the mine.

Gateroad developments and panel mining followed the mining sequence. Each panel in the model was mined gradually to reduce dynamic loading due to sudden removal of material. Details on the gradual reduction of traction on the mined-out boundary can be found elsewhere (Khademian et al., 2022).

RESULTS

First, the current mine layout was modeled, and the results of pillar pressure and floor heave were compared with the measurements. The pillars in the current design are 60-ft and 90-ft wide with a 220-ft-wide barrier center to center (Figure 5). Then, two alternative layouts were studied: one with 50-150-120-ft pillars and the other one with 50-50-320-ft pillars. In all scenarios, the distance between two longwall panel edges stays the same as 520 ft (158.1 m).

Current Layout

The 3DEC model with the current design was solved with mining the first panel. The pillar pressure and floor heave were recorded, after panel 1 was mined.

Pillar Pressure

Figure 6 shows the pillar pressure from BPCs and modeling results across pillars between panels 1 and 2.

The green curve in Figure 6 shows pillar pressure during development. The blue curve shows the pillar pressure after the panel 1 is mined. The BPCs were all initially set at 1,800 psi (12.4 MPa) during the development stage. The

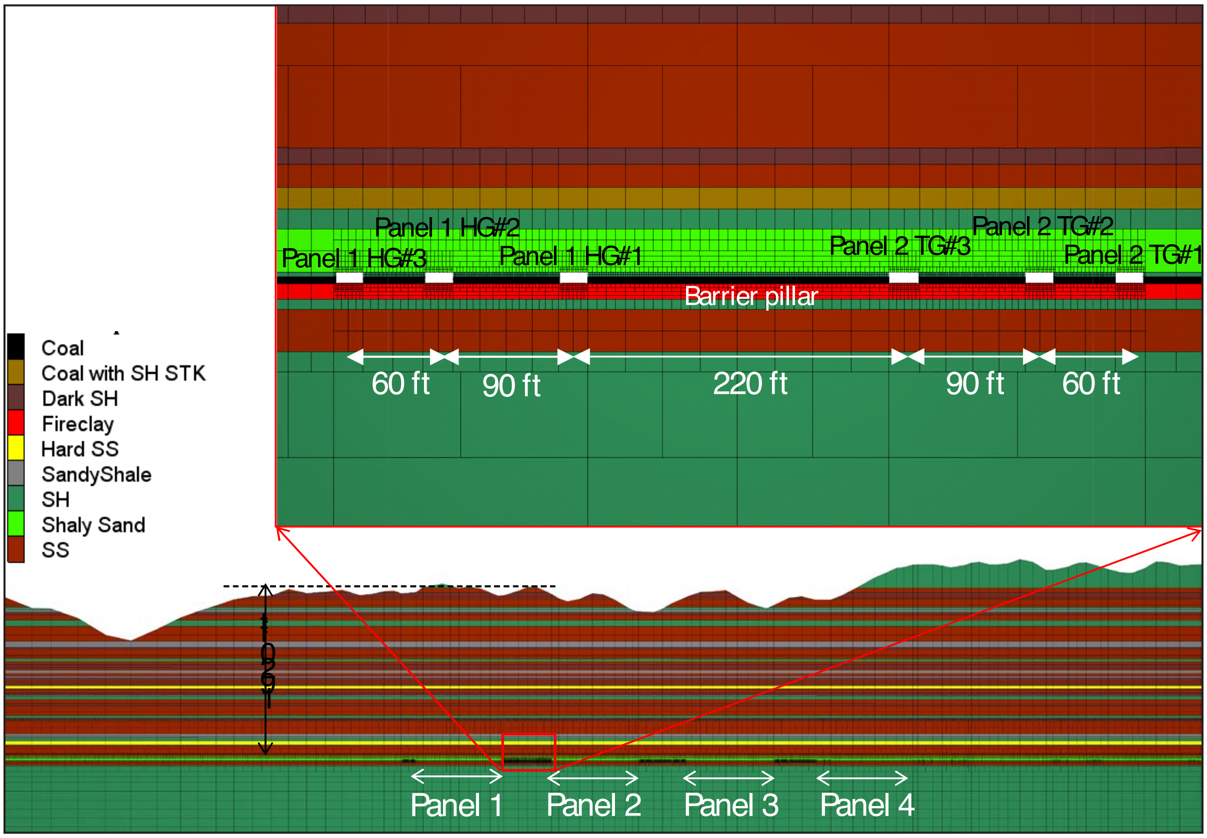

Figure 5. Model geometry in 3DEC

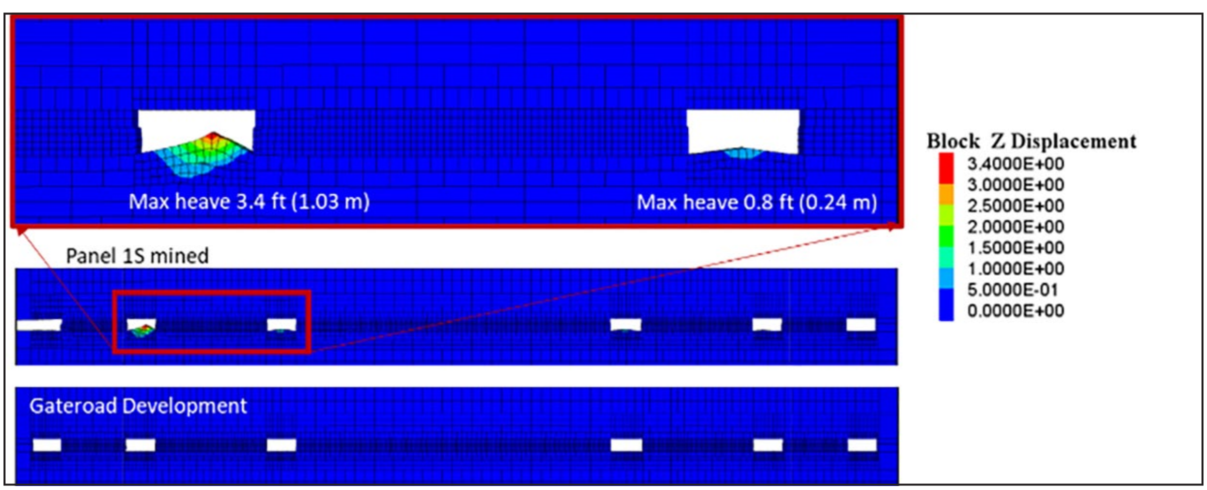

Figure 6. Pillar pressure obtained from 3DEC model and the measured values by BPCs

red dots show the BPC gauge values after panel 1 is mined. A comparison among the modeling results and BPC readings shows relatively good agreement.

The BPC readings in the stable and barrier pillars on the first panel headgate side show particularly less pressure than the modeling results. This is because we stopped recording data and removed dataloggers when the first panel reached the monitoring site. So, the full abutment loading was not captured by those BPCs.

The most important comparison is for the pressure in the stable and yield pillars in the tailgate of panel 2. Both modeling results and BPC readings show that there is load transfer from panel 1 mining to the panel 2 tailgate. The BPCs within the stable pillar in the tailgate of panel 2 in Figure 6 show an increase of 2,050 psi (14.1 MPa) and 2,440 psi (16.8 MPa). Figure 7 shows the BPC readings within the stable pillar in the panel 2 tailgate over time with panel 1 face locations.

The pressure in the big pillar (measured by BPC 4 and 5) started rising 250 ft (76 m) outby and kept increasing even 3,150 ft inby the face (the last measurement on 05/28/2024) to about 4,000 psi (28 MPa). As mentioned before, this means there was a 2,050 psi (14.1 MPa) to 2,440 psi (16.8 MPa) increase in pillar pressure from the development stage. From Figure 6, this pillar pressure increase was 1,160 psi (8 MPa) in the models. The BPCs in the yield pillar in the tailgate of panel 2 show an increase of 1,634 psi (11.3 MPa). The modeling results in this location show an increase of 971 psi (6.7 MPa) in this location. These results plus the author's observation of rib sloughing and mild floor heave (less than 1 ft (0.3 m)) in the tailgate of panel 2 confirmed that there is significant load transfer from panel 1 to panel 2.

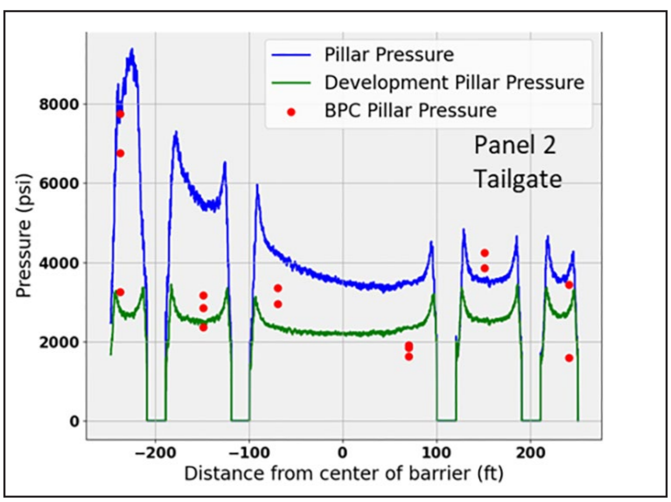

Figure 7. BPC readings in the stable pillar in the Panel 2 tailgate

Floor Heave

After mining panel 1, the heave in the floor was plotted. Figure 8 and Figure 9 show the modeling results for the profile of floor heave after mining panel 1. From the models, Panel 1 HG Entry #2 showed the highest heave of 3.4 ft (1.1 m). From the models, the load transfer to the panel 2 tailgate also caused floor heave of 0.8 ft (0.24 m) and 0.3 ft (0.1 m) in Panel 2 TG Entry #3 and #2, respectively.

Figure 10 shows initial results of LiDAR scanning. The point cloud shown in Figure 10 was collected during the March 2024 scanning event and is colored based on the height from an arbitrary floor line (red). The original

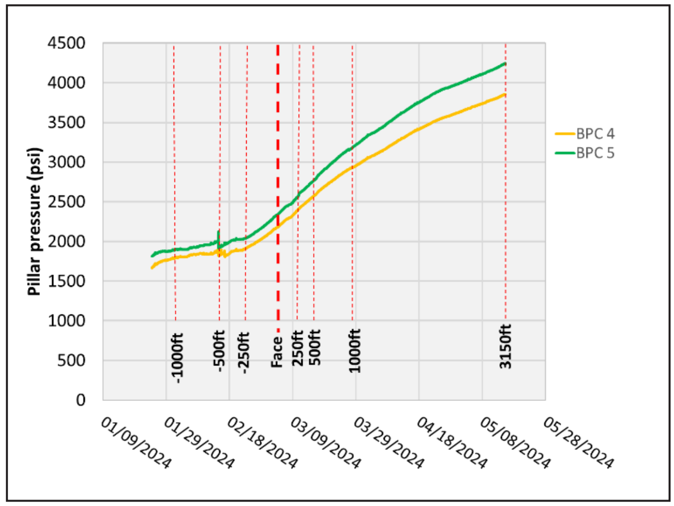

Figure 8. Floor heave profile from modeling results after panel 1 was completed

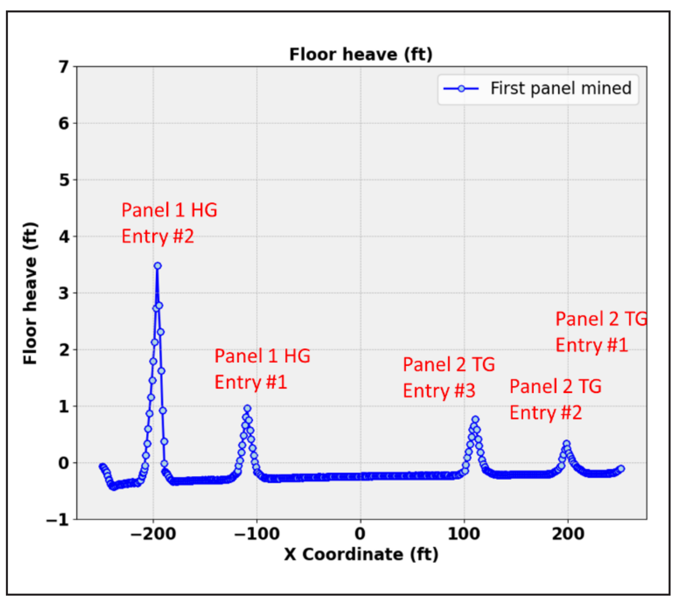

Figure 9. Floor heave profile from modeling results after panel 1 was completed

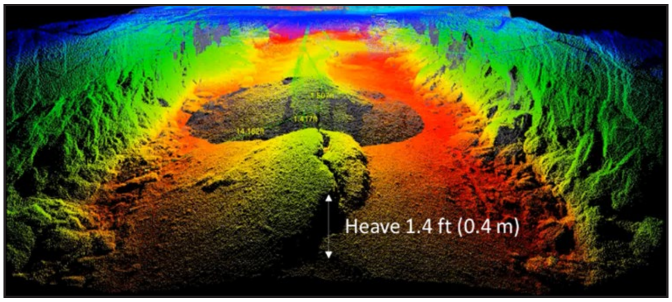

Figure 10. Floor heave profile from LiDAR scan in Entry 2H ~400 ft (121.6 m) outby the face

November 2023 point cloud was registered to the March 2024 point cloud and provides an original floor height. The comparison with the initial point cloud shows a heave of 1.4 ft (0.4 m) outby the face.

The heave magnitudes between the model and the LiDAR scans cannot be directly compared because the model is psedo-2D, and thus the heave profiles are related to the completion of panel 1. However, the LiDAR scans were taken around the instrumented pillars right before face mined by. However, the in-mine observation of the authors showed that heave further increased inby the face.

We also took scans of Entry #2 and 3 in Panel 2 tailgate side that can be directly compared with the modeling results, but at the time of writing this paper the LiDAR scan results were not fully processed.

The comparison between the modeling results and BPCs and LiDAR scans showed the model could have predicted the pillar pressure and floor heave. With this confidence, we evaluated alternative mine layouts with respect to floor heave and load transfer.

Alternative Layouts

Two alternative layouts were studied. One yield-stable-barrier and one yield-yield-barrier. Figure 11 shows the model geometry for the current and alternative mine layouts as constructed in the 3DEC software program.

The results for average pillar pressure across the pillars between the two panels are plotted in Figure 12. In Figure 12, YYB design increased barrier pillar pressure by 4%, while YSB design increases the barrier pillar pressure by 9%. Although YYB design has a wider barrier, the yield pillars transferred all loads to the barrier increasing its average load slightly higher than the current design.

In terms of load transfer to the panel 2 tailgate side, YYB design increases the transferred load by 11%, but YBS design reduces it by 5%. For load transfer calculation, the pillar pressure in pillar 2T in Figure 12 was the reference.

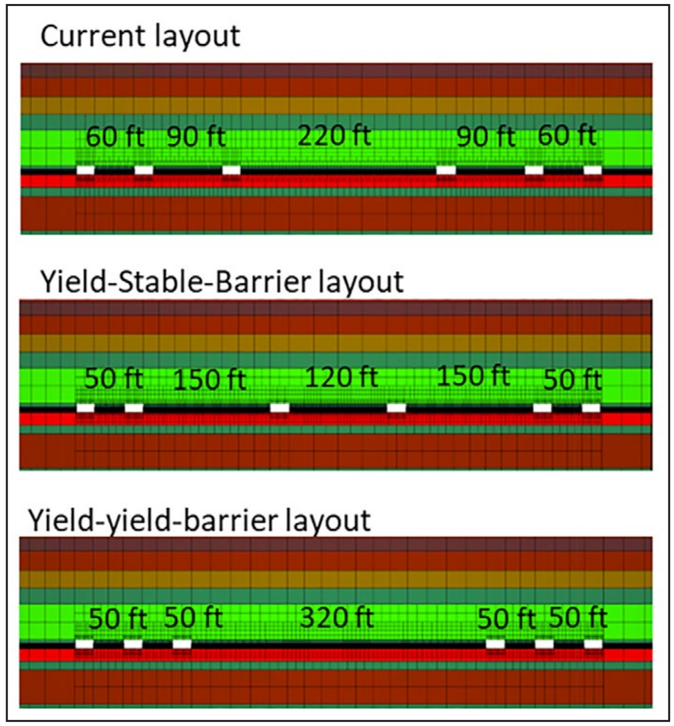

Figure 11. Current and alternative mile layouts constructed in 3DEC models

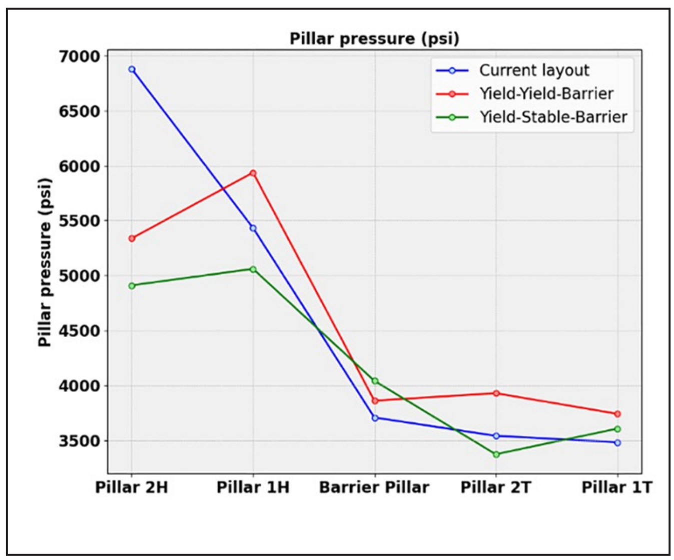

Figure 12. Average pillar pressure in different mine layouts

Figure 13 shows the floor heave after panel 1 was mined. The minimum floor heave in Entry 2H was for the current design. YYB and YSB led to the entry closure with the mining height of 7 ft (2.1 m). The minimum heave in the Entry 1H was for the YSB design, reducing the current heave by 72%. The largest heave is for the YYB design where the heave was almost doubled (85% increase from the current design).

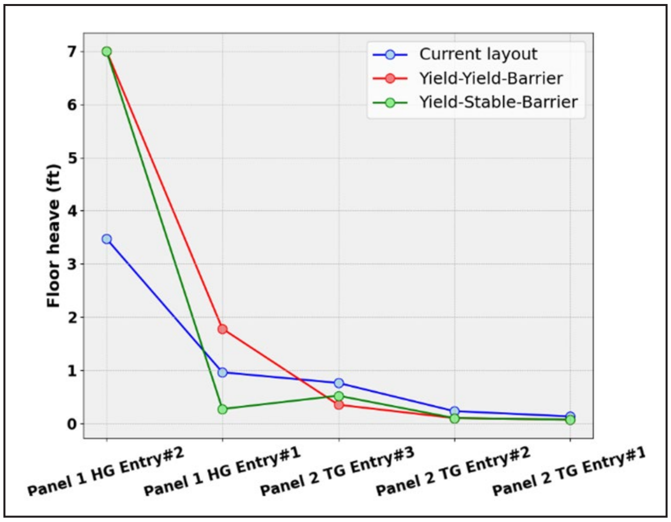

Figure 13. Average floor heave in different mine layouts

The heave in Entry 3T was reduced by the YBS design by 32%. The YYB design showed a further decrease in heave by 54%. Both the YYB and YSB designs reduced the heave in Entry 2T by 56%.

DISCUSSION

Extensive instrumentation of pillars and entries in a longwall mine was used to evaluate a new mine design. The BPC instrumentations show that there was a significant load transfer from the first panel to the second while the 220-ft-wide barrier pillar was supposed to isolate each panel. LiDAR scanning also showed significant floor heaves in the middle entry in the headgate of panel 1. A geomechanical model was developed and confirmed the instrumentation monitoring results of pillar pressure and floor heave. Then, two mine layout alternatives were evaluated in terms of load transfer and floor heave. The results showed that Yield-Stable-Barrier design with dimensions 50-150-120 ft led to minimum load transfer and floor heave in critical areas. The second design of Yield-Barrier with dimensions (50-50-320 ft) were shown to be close to the YSB design but with the advantage of less development time because it led to shorter crosscuts.

CONCLUSION

A study was conducted in a deep longwall mine in Virginia in a mining area with new single-panel-district design where each panel was isolated by a 220-ft-wide barrier pillar. The pillars in the headgate of the first panel and tailgate of the second panel were instrumented along with the barrier pillar separating the panels. The instrumentation results showed that there was a transfer of load from the first panel to the tailgate of the second panel during mining of the first panel. The results were also confirmed by geomechanical models that were then used to evaluate an alternative mine layout with respect to load transfer and floor heave.

Modeling results show that widening the barrier pillar by changing the layout to a two-yield pillar can reduce load transfer and floor heave in the entries of the next panel tailgate side. However, widening the stable pillar and narrowing the barrier pillar can further stabilize the entry while further reducing the load transfer to the second panel. Other operational and technical aspects need to be evaluated for comprehensive analyses of each layout. However, the results show how geomechanical models can be used for evaluating and thus optimizing mine designs, reducing ground control challenges and improving mine safety.

LIMITATIONS

This study is built on several, albeit reasonable, assumptions about the accuracy of instrumentation tools and rock mechanical properties used in the geomechanical models. Designs were evaluated based on only two criteria: pillar pressure and floor heave. However, many other aspects need to be evaluated such as mine ventilation, mine economy, development rate, seismic hazards, 3D model of the mining area and so on. In addition, conclusions in this paper may not be applicable to other mines with similar conditions. Mine layout effects on ground control challenges depend on the geology, overburden depth, surface topography, and mining conditions that need to be studied on a case-by-case basis.

DISCLAIMER

The findings and conclusions in this paper 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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