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# Analyzing Shale Gas Well Casing Deformation in Pittsburgh Seam Longwall Chain Pillars: A Case Study Integrating Numerical Methods and Field Monitoring

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**ABSTRACT:** In the Northern Appalachian region of the U.S., the coexistence of longwall coal mining and shale gas operations is a prominent feature. The gas wells in the vicinity of the longwall operations entail the potential for casing deformations arising from mining-induced subsidence and abutment stresses. Researchers at the Pittsburgh Mining Research Division (PMRD) of the National Institute for Occupational Safety and Health (NIOSH) have been employing a combination of field monitoring and calibrated numerical modeling methods to formulate engineering strategies for assessing the effects of longwall mining operations on gas well casing integrity and implementing measures to mitigate potential damage. This paper introduces the numerical modeling approach developed by PMRD researchers and verifies it by comparing the model's predictions of longwall-induced casing deformations with measurements from shale gas wells located in the gateroad chain pillar of the Pittsburgh coal seam longwall operation. The longwall panels adjacent to gas well chain pillars operate at a depth of approximately 313 meters, with a mining height of 2.1 meters and panel widths ranges between 450 to 480 meters. The gas well is constructed with fully cemented surface and intermediate casings, with the production casing left uncemented from the surface down to below the Pittsburgh coal seam. The model predicted that, following the first panel mining, the production casing would remain deformation-free, as the maximum predicted intermediate casing deformation falls below the annular space between the intermediate and production casing. This model prediction was subsequently confirmed through casing deformations monitored using a multi-finger caliper survey following the mining of the first panel.

## 1. INTRODUCTION

Pennsylvania is the second largest natural gas producer in the U.S., and since the 2005 shale gas boom, thousands of unconventional gas wells have been drilled through the Pittsburgh coal seam where the coexistence of longwall coal mining and shale gas operations is a prominent feature (Zhang et al., 2023). Pittsburgh coal seam longwall mines on average extract 460-m-wide and 4,000-m-long panels. The gas wells in the vicinity of these longwall operations entail the potential for casing deformations arising from mining-induced subsidence and abutment stresses, and if the deformations would be large enough to damage casing, that would lead to potentially hazardous conditions for the mine workers. The Pittsburgh Mining Research Division (PMRD) of the National Institute for Occupational Safety and Health (NIOSH) started a research project in 2016 to formulate engineering strategies for assessing the effects of longwall mining operations on gas well casing integrity and implementing measures to mitigate potential damage.

The engineering analysis of longwall-mining-induced gas well casing deformations were studied by Su (2016, 2017), Su et al. (2018, 2019), Scovazzo (2018), Zhang et al. (2019), Zhang and Su (2021), and Zhang et al. (2023). The key mechanism reported by all these authors is that the potential of casing deformation increases at the weak/strong strata contacts due to higher relative horizontal displacements along these weak interfaces. Su (2017) indicated that depth of cover influences this key mechanism. He showed that under deep cover, smaller lateral strata deformation is present in the overburden above the mining horizon due to higher confinement, but higher pressure and deformation at and below the coal seam can still lead to yielding of the well casing. Su et al. (2019) also showed that under a shallow cover stream valley, mining-induced subsurface relative horizontal displacements are higher. Later, Zhang and Su (2021) demonstrated that higher than expected horizontal movement can occur if water diffuses to claystone interfaces and lowers the frictional coefficient of the weak/strong strata contact.

Considering the complex nature of the gas well structure, overburden geology and longwall-mining-induced deformations/stresses and the uniqueness of each case, PMRD researchers have developed and been employing a combination of field monitoring and calibrated numerical modeling methods to investigate the interaction between overburden strata movements and casing deformations (Su 2016, 2017; Su et al. 2018, 2019; Zhang and Su 2021; Zhang et al. 2023). This paper presents analysis of the stability of a gas well drilled through a longwall abutment pillar of the Pittsburgh coal seam longwall operation, using the numerical modeling approach developed by PMRD researchers, and the verification of results by comparing the model's predictions of longwall-induced casing deformations with the 40-Arm Caliper survey measurements.

## 2. OPERATIONAL AND GEOLOGICAL CONDITIONS AT THE STUDY MINE

The study site consists of a shale gas well pad with four shale gas wells located in the abutment pillar between two adjacent longwall panels in the Pittsburgh coal seam. The longwall panels are approximately 450-m and 480-m wide, and the mining height is 2.1 m. The gateroad is a three-entry pillar layout that consists of center-to-center, 46-m-wide and 84-m-long abutment pillars, and 18-m-wide and 42-m-long smaller pillars. The gas wells setback distance to the 2B panel gob is 25 m. The overburden depth at the gas well location is 313 m. The longwall panel layout is shown in Fig. 1, and gateroad pillar layout and gas wells are shown in Fig. 2.

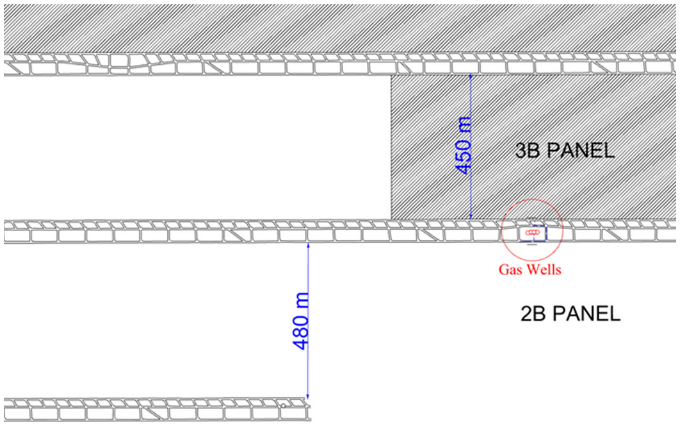

Fig. 1. Overview of the longwall layout and the location of the gas wells.

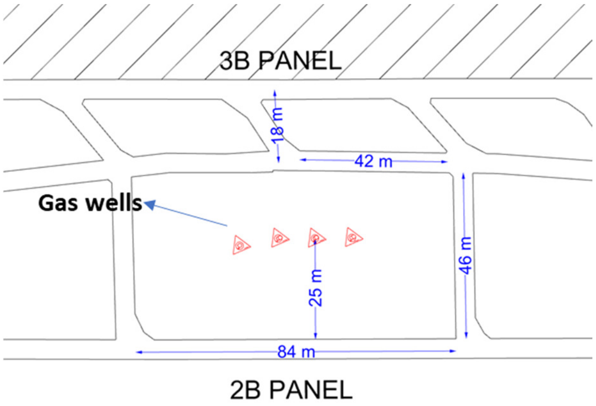

Fig. 2. The gateroad pillar layout and gas wells (triangles); the magenta-colored gas well was surveyed with 40-Arm caliper logging.

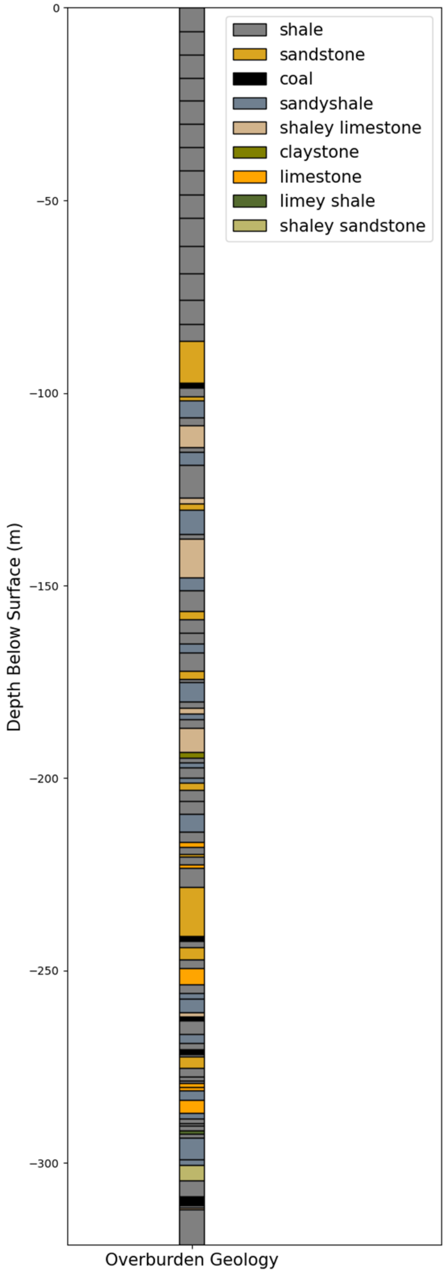

Fig. 3. Overburden geology interpreted from core hole data.

The overburden geology at the gas well site is interpreted from the core logs nearby the gas wells pad. The core log information was provided by the mine and gas well operators. The overburden at and near the gas wells is comprised of shale, sandyshale, limey shale, shaley limestone, shaley sandstone, sandstone, claystone, limestone, and sandstone strata. Fig. 3 shows the visualization of the overburden geological log that was used in the analysis. In the overburden, weak interfaces represent weak claystone and coal strata.

The gas wells were constructed with grade J-55 surface, grade MC50 intermediate, and grade P-110 production casings. The surface casing was fully cemented from surface to approximately 100 m below the coal seam, and the intermediate casing was also fully cemented from surface to more than 700 m below the coal seam. The production casing was uncemented from surface to more than 1,000 m below the seam level.  Table 1 summarizes the gas well casing specifications.

Table 1. Gas well casing specifications

| Casing | Size (cm) | Weight | Grade |
|---|---|---|---|
| Surface | 33.97 | 54.5# | J-55 |
| Intermediate | 24.45 | 40# | MC50 |
| Production | 13.97 | 20# | P-110 |

## 3. MODEL GENERATION FOR ESTIMATING LONGWALL-MINING-INDUCED GAS WELL DEFORMATIONS

Su (2016) developed a modeling approach that can be used to investigate the effects of longwall-induced stress and deformation on the stability of shale gas wells drilled through a longwall abutment pillar. He used finite element software ABAQUS to simulate the effect of longwall excavations on the mining-induced stresses and deformations. Zhang et al. (2019) used FLAC3D and a similar approach to Su (2016) to develop a standardized procedure to realistically simulate the influence of longwall mining on the stability of gas wells in chain pillars. In this method, depending on the relative location of the gas well chain pillar to panel mining, simulation can be performed in 2D slice or full 3D. If the gas well is far away from the startup or recovery rooms, 2D slice can be used in the simulation. In this case study, since the gas wells are located close to the middle of the panel, 2D model geometry was generated.

The overburden strata are modeled by ubiquitous joint material from surface to below the mining horizon, and geology at the site is interpreted from the core hole data as shown in Fig. 3. Recommended overburden strata rock and weak interface properties for the Pittsburgh coal seam mines were published by Zhang et al. (2019 and 2023). Zhang et al. estimated these field scale mechanical properties from analysis of the laboratory tests and back analysis of the subsidence and mining-induced stress distributions from different field measurement case studies. Table 2 summarizes the field scale mechanical properties used in the simulation of the overburden strata.

Table 2. Overburden strata rock properties used in the model.

| Rock Type | Elastic Modulus (GPa) | Poisson's Ratio | Cohesion (MPa) | Friction Angle (deg.) | Tensile Strength (MPa) |
|---|---|---|---|---|---|
| Coal | 1.72 | 0.3 | 1.86 | 28 | 0.28 |
| Claystone | 4.34 | 0.3 | 1.29 | 28 | 0.34 |
| Limey shale | 7.24 | 0.25 | 6.78 | 35 | 2.60 |
| Shale | 5.79 | 0.25 | 5.86 | 35 | 2.25 |
| Sandyshale | 5.79 | 0.25 | 5.86 | 35 | 2.25 |
| Sandstone | 5.79 | 0.25 | 8.96 | 35 | 3.44 |
| Shaley limestone | 8.69 | 0.22 | 7.24 | 38 | 2.97 |
| Shaley sandstone | 7.24 | 0.22 | 5.86 | 38 | 2.40 |
| Siltyshale | 5.79 | 0.25 | 5.86 | 32 | 2.11 |

To predict the response of overburden strata and gas well casing deformations reliably, it is important to model the gob response realistically. Zhang et al. (2019) used a strain hardening model to simulate the gob compaction. Eq. 1 is the hyperbolic function, derived by Salamon (1990), used to simulate the strain hardening stress-strain relationship. In this equation "$\sigma(\epsilon)$" is the vertical gob element stress (MPa), "$\epsilon$" is vertical gob element strain, "$b$" is the maximum strain parameter related to void ratio and "$a = \sigma\left(b = \frac{\epsilon}{2}\right)$" (MPa).

$$\sigma(\epsilon) = \frac{a \times \epsilon}{b - \epsilon} \quad (1)$$

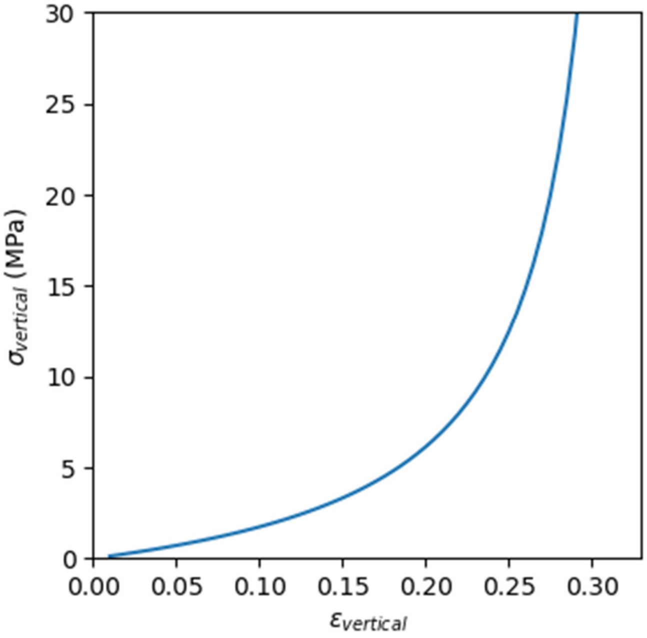

Fig. 4. Stress-strain behavior of strain hardening gob element used in the model, a = 4.0 MPa and b = 0.33.

Su (1991) simulated the behavior of the gob, which is assumed to be formed under an initial bulking factor of 1.5 based on observation of caving height in boreholes, representing a maximum vertical strain of 33% and a caving height equal to three times the mining height. Su used this approach very successfully for many years for estimating surface subsidence and pillar stresses for several longwall mines in the Northern and Central Appalachian regions. Zhang et al. (2019) and Tulu et al. (2017) adapted this approach to simulation of the gob material by assigning 33% to maximum strain parameter "b". For achieving realistic surface subsidence and abutment overburden stress distribution, the "a" parameter is set to 4.0 MPa. Fig. 4 visualizes the stress-strain behavior of a gob element simulated in the model.

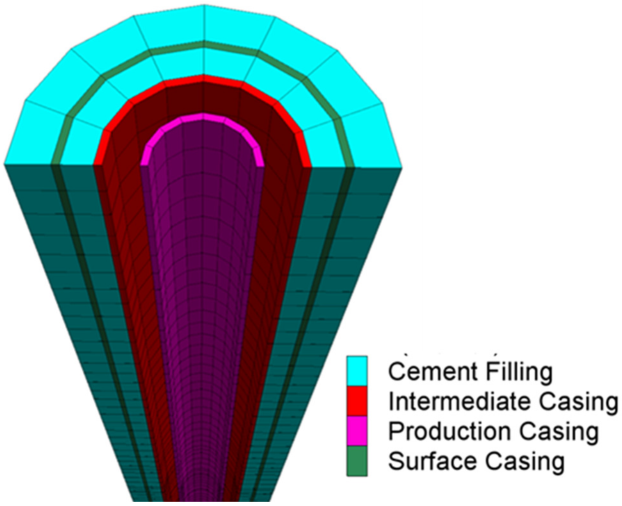

Fig. 5. Gas well model geometry created to simulate casing deformations.

Fig. 5 shows the gas well geometry modeled to simulate the deformation of the gas well casings. Gas well model geometry was constructed with three casings: fully cemented surface and intermediate casings and the uncemented production casing through the Pittsburgh coal seam. The steel casings were modeled with the von Mises material model, and the cement fillings were modeled with the Mohr-Coulomb material model. The gas well casings were modeled according to their construction and specifications listed in Table 1 and Table 3. The gas well was constructed into the model before the gateroads were excavated.

Table 3. Gas well casing model parameters.

| Casing | Wall Thickness (cm) | Elastic Modulus (GPa) | Poisson's Ratio | Yield Strength (MPa) |
|---|---|---|---|---|
| Surface | 0.97 | 200 | 0.3 | 379.2 |
| Intermediate | 1.00 | 200 | 0.3 | 344.7 |
| Production | 0.92 | 200 | 0.3 | 758.4 |

The longwall panel layouts were simulated according to the operational parameters discussed in Section 2 of this paper. Fig. 6 shows the cross-sectional view of the FLAC3D model. Only half of the gas well casings were implemented with a symmetry boundary condition.

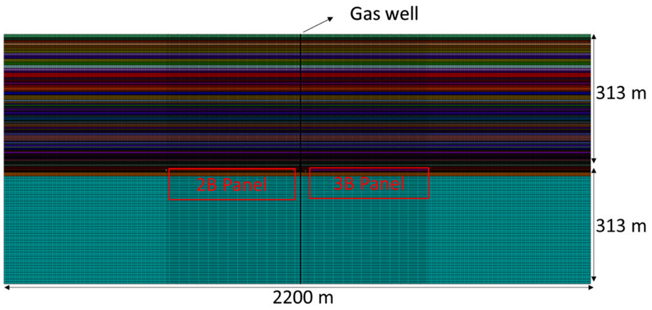

Fig. 6. Cross-sectional view of the FLAC3D model.

## 4. MINING INDUCED STRESS, SUBSIDENCE AND CASING DEFORMATION RESULTS

Fig. 7 shows the predicted vertical stress distribution across the chain pillars: the red line is in-situ stress distribution; blue and green lines are stress redistribution after 1st panel and 2nd panel mining. The horizontal axis in Fig. 7 represents the distance from the gas well, and gas well is located at the origin (x = 0). The vertical stress distributions after first and second panel mining agree with the stress measurements from a Pittsburgh coal seam longwall mine with a similar overburden depth (Zhang et al., 2023; Su et al., 2018). The vertical stress at the gas well location increased 3.6 MPa after first panel mining and 10.4 MPa after second panel mining from in-situ stress level.

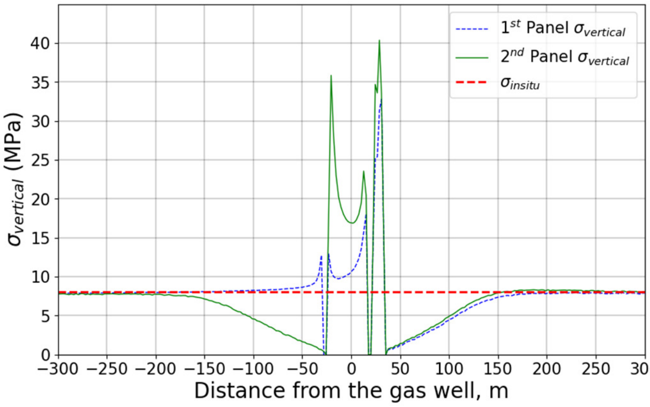

Fig. 7. Vertical stress distribution before and after longwall mining.

Fig. 8 shows estimated final surface subsidence across the gateroad pillars and longwall panels after first and second panel mining. The gas well is located at the origin of the horizontal axis. The blue line represents final subsidence after first panel mining, and the green line represents final subsidence after second panel mining. The model predicted a supercritical subsidence profile with a maximum subsidence of 1.38 m. The surface subsidence predicted at the gas well location (x=0) is about 5.7 cm after first panel mining and about 20 cm after second panel mining. These predicted subsidence values are within the range of the measured and predicted surface subsidence published by Zhang et al. (2023) on longwall panels operated in the Pittsburgh coal seam with similar mining conditions and overburden depth.

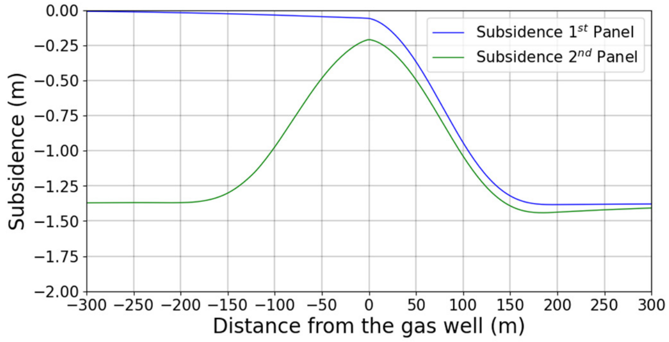

Fig. 8. Surface subsidence after 1st and 2nd panel mining.

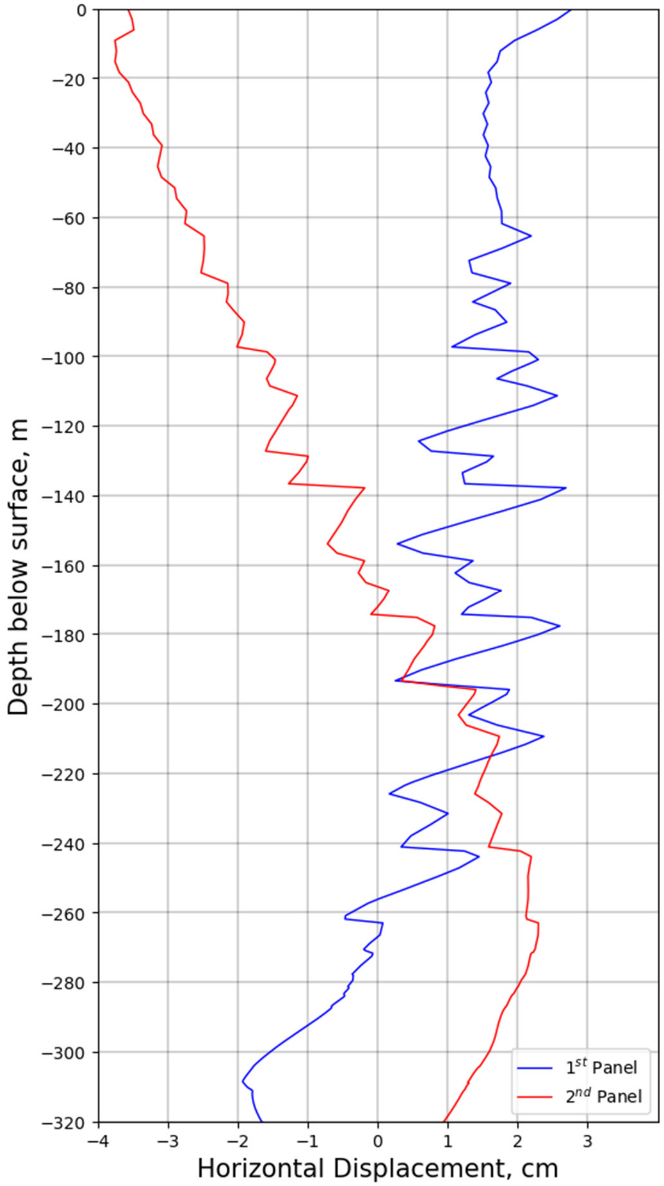

Fig. 9. Horizontal displacement along the intermediate casing.

Fig. 9 shows the longwall-mining-induced horizontal displacement computed by the model along the intermediate casing. The blue and red lines represent the horizontal displacement along the intermediate casing after first and second panel mining. The largest relative horizontal displacement along the intermediate casing was computed as 2.08 cm after first panel mining and 3.63 cm after second panel mining at 138 m below the surface. The annular space between the production and intermediate casings is 8.47 cm. Since the production casing is uncemented in this well and predicted intermediate casing deformations, 2.08 cm and 3.63 cm, are significantly lower than the annular spacing, model results indicated that there is not any deformation expected along the production casing. Fig. 10 shows the 40-Arm Caliper survey results after the first panel mining. Fig. 10 shows the size and shape of the production casing over its length, and the results indicate that there is not any deformation along the production casing.

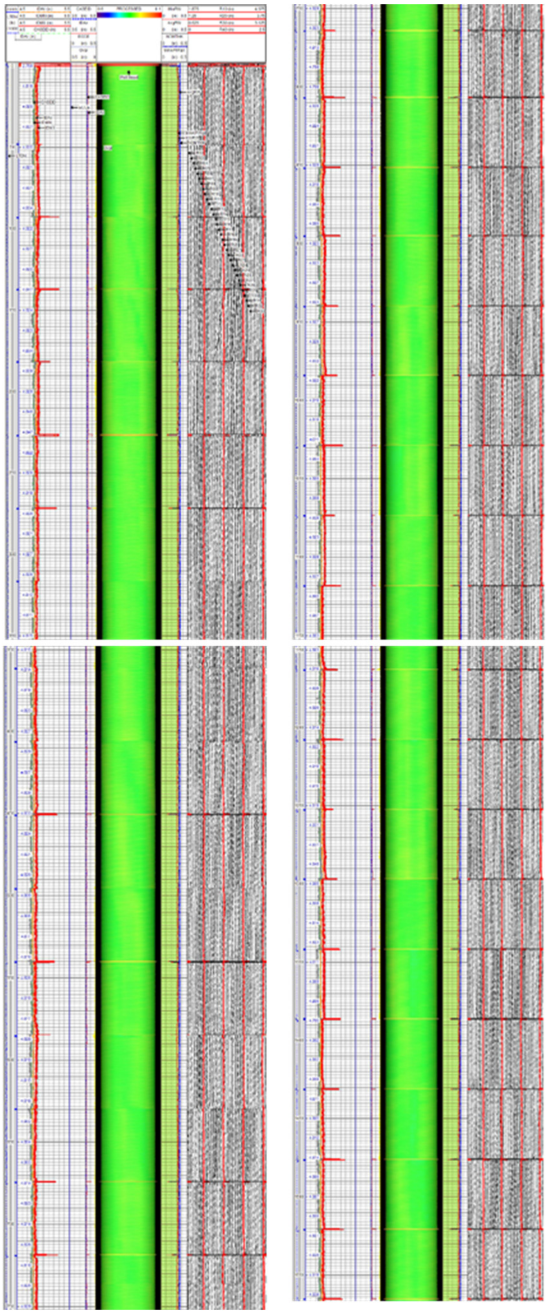

Fig. 10. 40-Arm Caliper Survey Results after First Panel Mining.

## 5. LIMITATIONS OF THE STUDY

This paper represents a site-specific case study. The results and conclusions presented in this paper depends on the site-specific geology, stress state and operational parameters. More case studies and field measurements at similar geological, stress and operational conditions are needed for definitive conclusions to ensure the findings from these studies are repeatable. FLAC3D simulation results are dependent on the input parameters used, and if these parameters applied to other cases, results need to be validated by actual field data.

## 6. CONCLUSIONS

This paper presented the application of the numerical modeling approach developed by PMRD engineers to evaluate longwall-induced casing deformations from shale gas wells located in the gateroad chain pillar of the Pittsburgh coal seam longwall operation. The casing deformations computed by the model were compared with the 40-Arm Caliper survey results to verify the model results.

The model results indicated that the longwall-mining-induced deformation of gas well casings can be simulated satisfactorily with the modeling approach developed by Zhang et al. (2019 and 2023). The paper also provides a basic set of input data and a modeling approach for overburden strata, gas well casings, and gob material. The key conclusion from this study is that there was no production casing deformation predicted along the uncemented production casing after first and second panel mining, which demonstrates the benefit of leaving the production casing uncemented.

## DISCLAIMER

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