

SHALE GAS WELL STABILITY UNDER THE INFLUENCE OF UNDERGROUND LONGWALL COAL MINING

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ABSTRACT

This paper presents the results of a unique study conducted by CDC/NIOSH/PMRD from 2016 to 2020 to evaluate the effects of longwall-induced subsurface deformations on shale gas well casing integrity and underground miner safety and health. Results from the NIOSH instrumentation sites are compared to the results from a previous study by the coal and gas industries, which clearly indicate that under shallow and medium covers, the measured horizontal displacements within the abutment pillar are one order of magnitude higher than those measured under deep cover. Detailed evaluations of the 1957 PADEP Gas Well Pillar Regulation, which has been used by MSHA and seven other states, indicate that the regulation can be applied to longwall mining if the depth of cover is less than 750 feet. Preliminary guidelines on longwall-induced deformations, casing and cementing alternatives, and gas well setback distances under chain pillar and barrier pillar scenarios are proposed.

INTRODUCTION

Due to a recent shale gas boom, approximately 1,500 unconventional shale gas wells have been drilled through active and future coal reserves in Pennsylvania, West Virginia, and Ohio over the past 17 years. These shale gas wells have penetrated both current and future Pittsburgh Seam coal reserves. These unconventional gas wells, whether tapped into the Marcellus or Utica formations, contain very high gas pressure. Strata deformations associated with underground longwall coal mining could induce high stresses and deformations in the shale gas well casings, which in certain situations could compromise the mechanical integrity of the production, intermediate, and coal protection casings. Damaged well casings could potentially introduce high-pressure, high-volume explosive gas into underground mine workings, which could jeopardize underground miners' safety and health.

To provide critical scientific data to the stakeholders, which includes the Mine Safety and Health Administration (MSHA), the Pennsylvania Department of Environmental Protection (PADEP), the West Virginia Department of Natural Resources (WVDNR), the Ohio Department of Natural Resources (OHDNR), coal operators, and gas operators, NIOSH initiated a research project in 2016 to evaluate the effects of longwall-induced deformations on shale gas well casing stability under deep as well as shallow covers. The effects of longwall-induced subsurface deformations on shale gas well casing stability under deep cover were presented by NIOSH researchers in 2018 (Su et al., 2018a and 2018b), and the results from a 2018 NIOSH research study focusing on the longwall-induced subsurface deformations and permeability changes under shallow cover, specifically near a major stream valley, were presented in 2019 (Su et al., 2019a and 2019b) and 2020 (Su et al., 2020a and 2020b; Zhang et al., 2020). This paper summarizes the most important findings of longwall-induced subsurface deformations over the past decade and focuses on providing preliminary guidelines on longwall-induced deformations, casing and cementing alternatives, and gas well setback distances under chain pillar and barrier pillar scenarios.

GEOTECHNICAL INSTRUMENTATION

Geotechnical instrumentations were conducted at three test sites: deep cover, medium cover, and shallow cover test sites. The deep cover test site (Su et al., 2018a and 2018b) was located over a southwestern Pennsylvania coal mine employing 1,500-foot-wide longwall panels to extract coal from the Pittsburgh seam, which lies 1,185 feet below the surface. A three-entry longwall gate-road system of 70-ft x 150-ft centers was employed at the mine. The medium cover test site (Su, 2016) was also located over a southwestern Pennsylvania coal mine employing 1,500-foot-wide longwall panels to extract coal from the Pittsburgh seam, which lies 604 feet below the surface. This study was carried out by the coal industry, gas industry, the Marcellus Shale Coalition, and the Pennsylvania Coal Association in 2013 and 2014. A three-entry longwall gate-road system of 60-ft x 125-ft centers was employed at the mine. The shallow cover test site (Su et al., 2019a and 2019b) was also located over a southwestern Pennsylvania coal mine employing 1,500-foot-wide longwall panels to extract coal from the Pittsburgh seam, which lies 482 feet below the surface. A three-entry longwall gate-road system of 60-ft x 125-ft centers was employed at the mine. Figure 1 illustrates the layout of the longwall panels and the locations of the surface, subsurface, and underground instrumentation at the deep, medium, and shallow cover test sites. Subsurface inclinometer monitoring holes drilled over the center of the 125-ft x 275-ft centers abutment pillar and borehole pressure cells installed into the 125-ft x 275-ft centers abutment pillar were carried out at all three test sites. For the medium cover site, four test wells were also installed. The test wells only had three casings, namely, surface, water, and coal protection casings. Pre-mining, post-first-panel mining, and post-second panel mining 60-arm caliper logs were conducted in the four test wells. For the shallow cover test site, three permeability test holes were installed to measure longwall-induced permeability changes within the abutment pillar. In addition to the subsurface and underground measurements, pre- and post-longwall surface subsidence measurements were conducted to corroborate surface responses with subsurface and underground responses.

INSTRUMENTATION SITE GEOLOGY

Detailed overburden geology at the deep cover, medium cover, and shallow cover test sites down to the coal seam level were compiled by correlating a test site gamma log and a nearby core hole. The overburden geology at the three test sites contains many strong-to-weak rock interfaces, which have been demonstrated to have major influences on longwall-induced stresses and deformations from ground control research conducted over the past 30 years. In particular, the presence of a weak Uniontown Coal Zone above the A-, B-, C-, D-Limestone sequence and the presence of clayey shale in the Sewickley Coal Zone sandwiched between the Benwood Limestone and the Sewickley Limestone indicate potential planes of weakness where substantial longwall-induced subsurface bedding plane movements may occur.

3D FINITE DIFFERENCE SIMULATIONS

FLAC3D finite difference simulations (Itasca, 2017) were conducted and analyzed to evaluate the effect of longwall excavations on the induced stresses and deformations within the gate-road abutment pillar. Detailed overburden geology, compiled at the individual test site, was the primary model input. Specifically, over 120 weak-to-strong rock interfaces were present and simulated in each of the three test site models, which employed over 400,000 zones. A hypo-elastic longwall gob model with a maximum deformation of 25% was employed in the FLAC3D models. The primary goal of the simulations was to duplicate measured surface subsidence, measured subsurface in-place inclinometer displacement, and measured underground coal pillar pressure increase. The FLAC3D finite difference program was selected since it has been calibrated and verified with field data from the Pittsburgh seam.

RESULTS OF GEOTECHNICAL INSTRUMENTATION AND 3D NUMERICAL ANALYSES

Figure 2 shows a measured surface subsidence profile over the supercritical panel at the shallow-cover test site. With supercritical panel width, longwall-induced surface subsidence is expected to reach the maximum possible value of $0.667 \times$ mining height at $0.3 \times$ depth of cover from the headgate and tailgate panel edges. Figure 2 also shows the FLAC3D-calculated surface subsidence profile and illustrates good agreement between measured and calculated subsidence profiles. Typically, the measured and calculated subsidence profiles are in excellent agreement except near the panel edge, where a slight discrepancy might exist due to topography and under-represented planes of weakness in the overburden. Measured and calculated surface subsidence profiles under deep and medium covers, although not shown here due to page limitation, follow the same supercritical panel rule and exhibit the same excellent agreement.

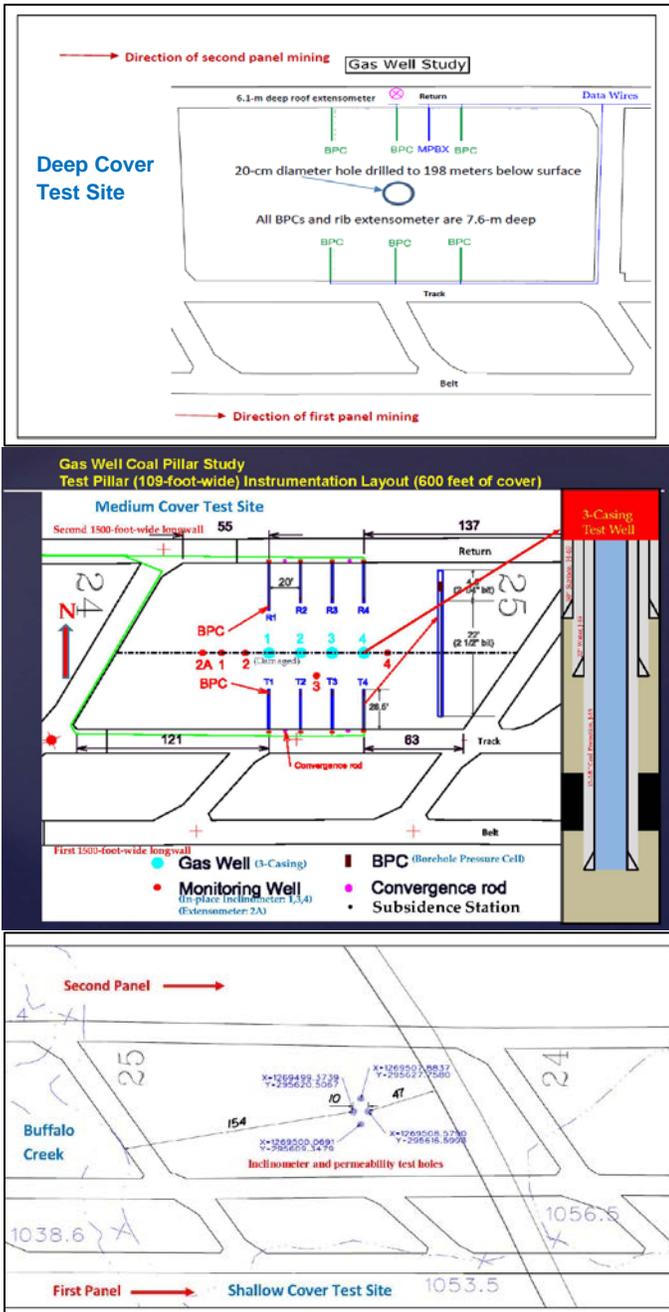
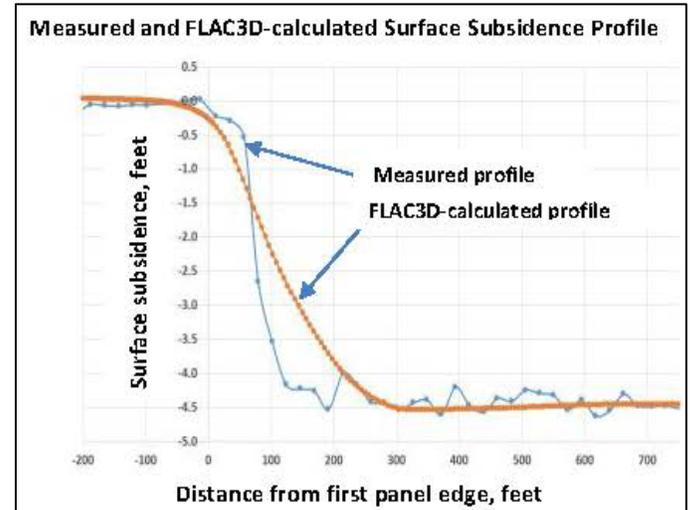


Figure 1. Surface, subsurface, and underground instrumentation layout at the deep, medium, and shallow cover test sites.



Figures 2. Measured and calculated surface subsidence at the shallow cover site.

Figures 3A, 3B, and 3C illustrate measured in-place inclinometer casing displacements at the deep, medium, and shallow cover test sites. Figures 3A, 3B, and 3C also include computed in-place inclinometer displacements for comparison. Overall, FLAC3D simulations provided reasonable agreement with measured inclinometer displacements. At the medium cover test site, longwall-induced lateral displacements in the overburden were measured by a suite of 60-arm caliper logs. At the shallow cover test site, the inclinometer sensors were purposely oriented along the direction of longwall mining to capture the influence of the east-west regional horizontal stress under the shallow stream valley environment. Figure 3C also shows the FLAC3D-calculated inclinometer displacements perpendicular to and along the direction of longwall mining. The calculated maximum lateral displacements perpendicular to and along the direction of longwall mining occur at the 400-ft depth horizon and are 6.6 inches and 0.7 inch, respectively. The calculated lateral displacements in the direction of longwall mining are in general agreement with the measured in-place inclinometer displacements. Although not measured in this field study, the FLAC3D-calculated inclinometer displacements perpendicular to the direction of longwall mining are comparable to but slightly higher than those at the medium cover test site (Figure 3B) (Su, 2016) and are one order of magnitude higher than those measured at the deep cover test site (Figure 3A) (Su, et al., 2018a and 2018b). This is expected since, under deep cover, for the same distance above the mining horizon, the weak-to-strong rock interfaces are subject to higher vertical loads under deep cover, which are expected to hinder lateral displacement. It is important to recognize that, while the FLAC3D calculates horizontal displacements along every individual plane of weakness, the in-place inclinometers have a 10-ft gage length and thus average horizontal movement over the 10-ft span. Figures 4A, 4B, and 4C show the

measured pillar pressure increases at the three test sites. Figures 4A, 4B, and 4C also show the comparison between measured and computed pillar pressure increases, which indicates excellent agreement between the measured and computed pillar pressure increases.

Table 1 summarizes the effects of cover depth on longwall-induced maximum subsurface deformations and abutment pressures.

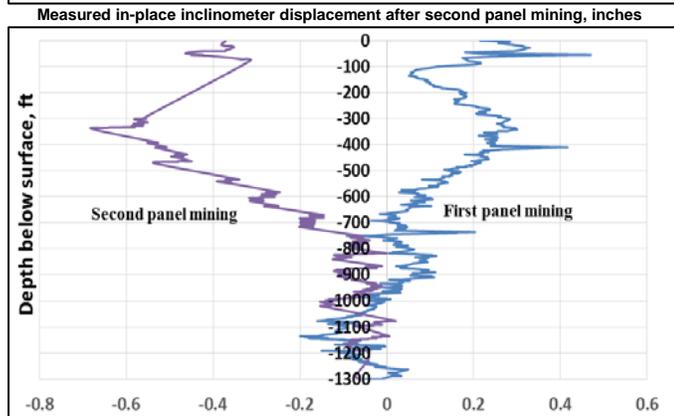
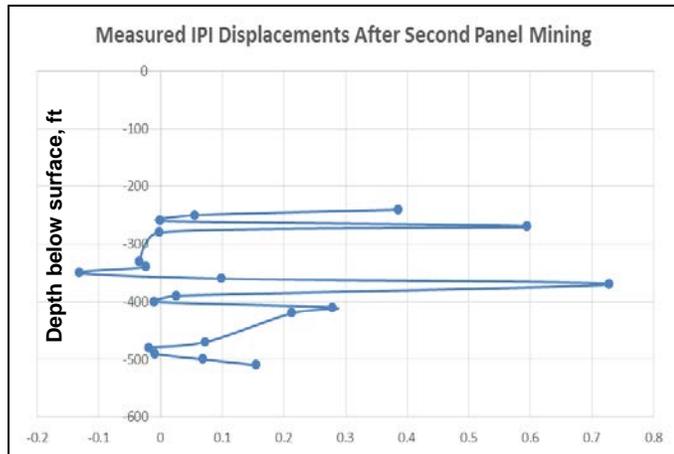


Figure 3A. Measured and calculated in-place inclinometer displacements at the deep cover site.

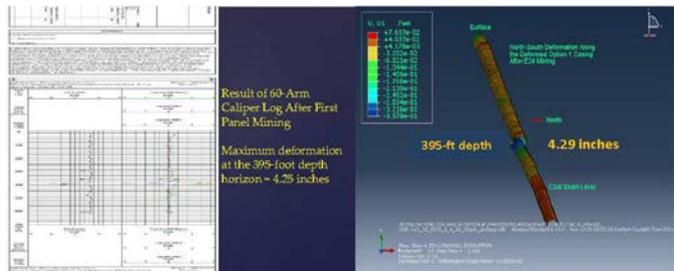


Figure 3B. Computed and measured lateral casing deformation (via 60-arm caliper log) at the medium cover site.

EVALUATION OF THE 1957 PADEP GAS WELL PILLAR GUIDELINES

The 1957 PADEP Gas Well Pillar Guidelines were developed by statistically fitting the failure data and drawing an 8-degree support angle. Majority of the failures occurred within overburden depths of 200-650 ft. For overburden depth greater than 650 ft, the guidelines require a solid pillar area of 10,000 square ft with a minimum total bearing area of 40,000 square ft. The 1957 guidelines were developed for gas well pillar sizes in room and pillar mining with full recovery, and later were also applied to gas well pillars in longwall mining.

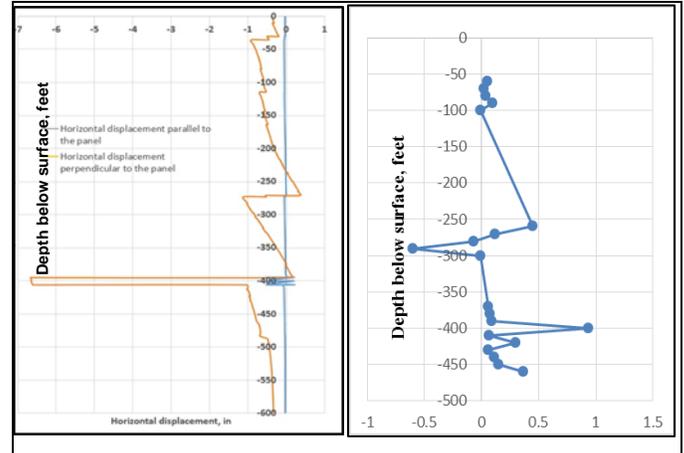


Figure 3C. Measured and computed inclinometer casing displacements perpendicular to and parallel to the direction of longwall mining at the shallow cover site.

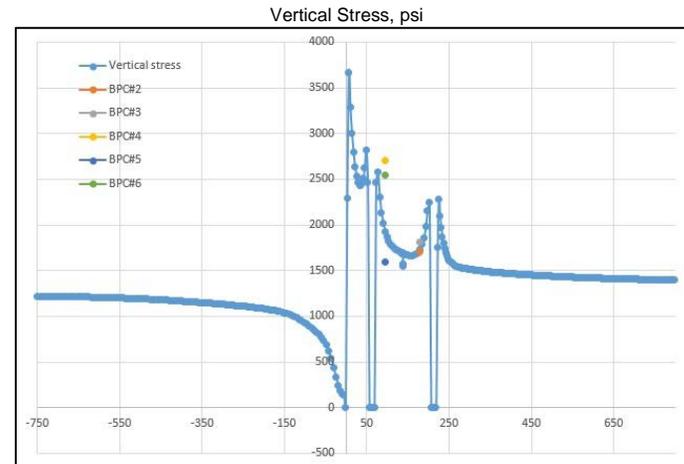


Figure 4A. Measured and computed pillar pressures at the deep cover test site.

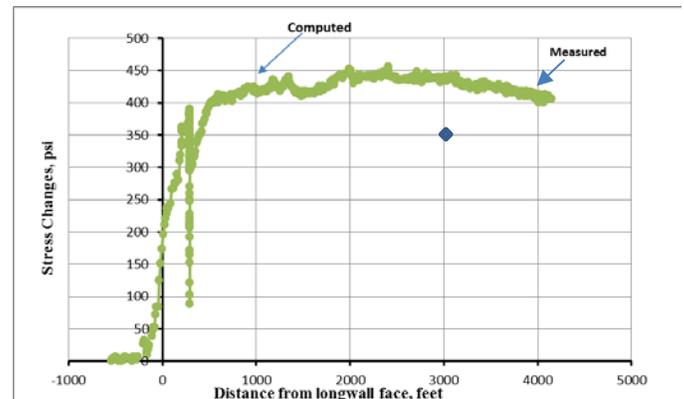


Figure 4B. Measured pillar pressures after first panel mining at the medium cover test site.

Figure 5 indicates that for overburden depths less than 750 ft, conventional gas well casings stay below the rated casing yield strength near the coal seam horizon.

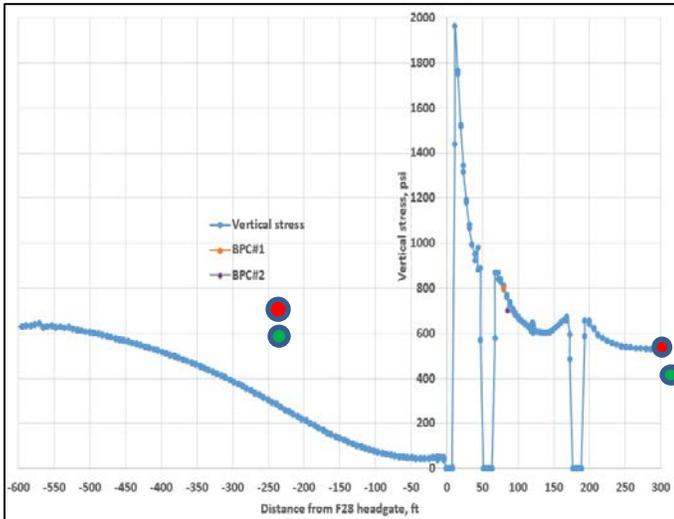


Figure 4C. Comparison of measured and computed pillar pressures at the shallow cover test site (second panel mining).

Table 1. Longwall-induced maximum subsurface overburden deformations and abutment pressure versus depth of cover.

Depth of cover, meter (feet)	Maximum subsurface deformations, mm (inches)	Maximum abutment pressure, MPa (psi)
361 m (1185 feet)	19 mm (0.75 in)	17.2 MPa (2494 psi)
184 m (604 feet)	108 mm (4.25 in)	2.6 MPa (400 psi)
147 m (482 feet)	168 mm (6.6 in)	0.7 MPa (102 psi)

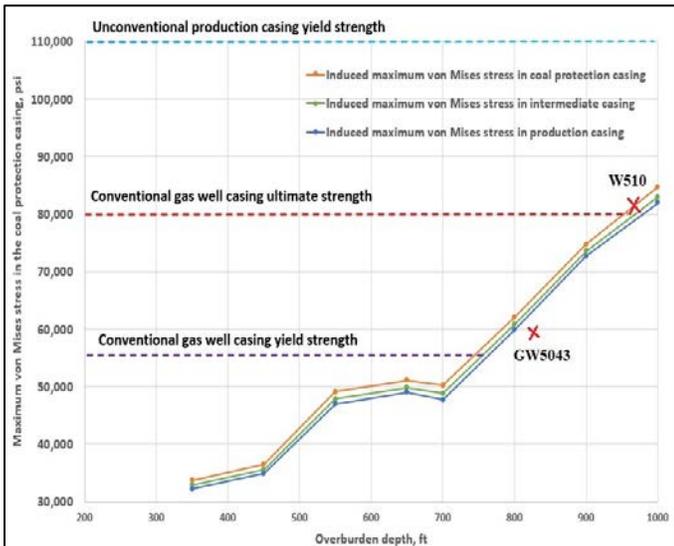


Figure 5. Effect of cover depth on longwall-induced production casing stress

However, for overburden depths greater than 800 ft, conventional gas wells casings could yield and subject to large deformations even if chain pillars meet the 1957 guidelines. For unconventional wells, on the other hand, the P-110 production casing does not yield with chain pillar size meeting the 1957 guidelines.

Key takeaways from the FLAC3D evaluations of the 1957 PADEP Gas Well Pillar guidelines are: (1) the great majority of the conventional well failures in the 1957 study occurred above, within, and below the coal seam, (2) the 1957 guidelines greatly reduced the number of gas well failures by making the gas well pillars larger, reducing the pillar and floor pressure around the gas wells, and increasing the setback distance, (3) the 1957 guidelines for gas well pillars in room and pillar mining are not conservative in all cases; Under deeper cover, with pillared gob on three or four sides, gas well

failures could still occur, (4) when the 1957 guidelines are applied to longwall chain pillars, modeling results indicate that conventional and unconventional gas wells are generally stable for overburden depth less than 750 ft; risk of gas well casing failure may exist due to potential horizontal strata movement, (5) for longwall mining under overburden depth greater than 750 ft, modeling results indicate that conventional gas wells could be damaged even if chain pillar sizes around the wells meet the 1957 guidelines, and (6) modeling results indicate stable P-110 production casing for unconventional gas wells meeting the 1957 guidelines (Figure 5).

FLAC3D MODELING OF WELL CASING STABILITY

A few FLAC3D finite difference models, Figures 6A and 6B, were also constructed to evaluate the potential effects of longwall-induced stresses and deformations within the longwall abutment pillars on shale gas well casing integrity.

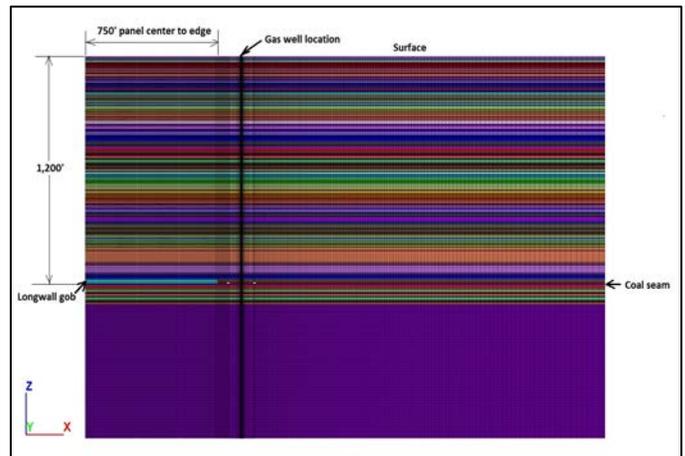


Figure 6A. 3D finite difference model of a gas well in a longwall abutment pillar.

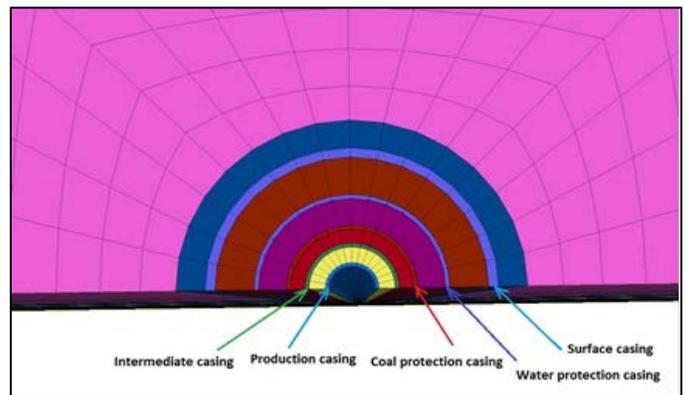


Figure 6B. Detailed 3D finite difference model of a gas well in a longwall abutment pillar.

Longwall-induced Casing Stresses

It is well known that overburden depth and its associated geology have a significant influence on longwall-induced stresses and deformations. The calibrated FLAC3D models were employed to evaluate the effect of longwall-induced stresses and deformations and their impact on gas well casings under deep, medium, and shallow cover conditions. Figures 7A, 7B, and 7C show that, at the three test sites and with the presence of major soft-to-hard rock interfaces, the longwall-induced deformations caused the production casings to deform. However, the resulting von Mises stresses in the production casings at the three test sites never exceeded the rated yield strength of the P-110 production casing, which is 110,000 psi. Additionally, the casing stress analysis for the medium cover test site (Figure 7B) illustrates that leaving the intermediate and/or production casings

uncemented from 50 feet below the coal seam to surface effectively uncouples the casings from longwall-induced ground movements.

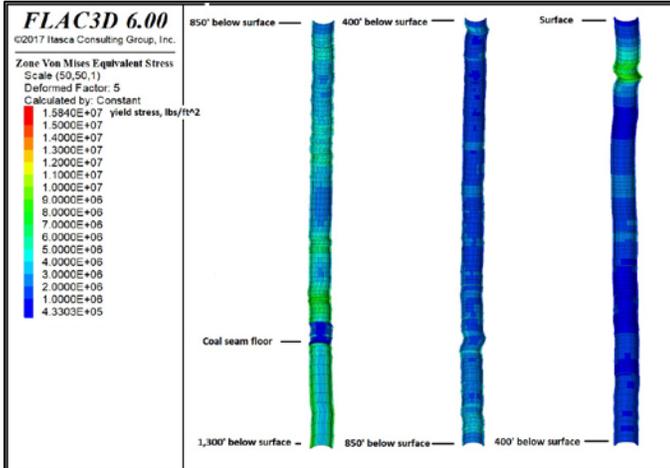


Figure 7A. Longwall-induced von Mises stress in the production casing (grouted to the surface) at the deep cover site (1,185 feet).

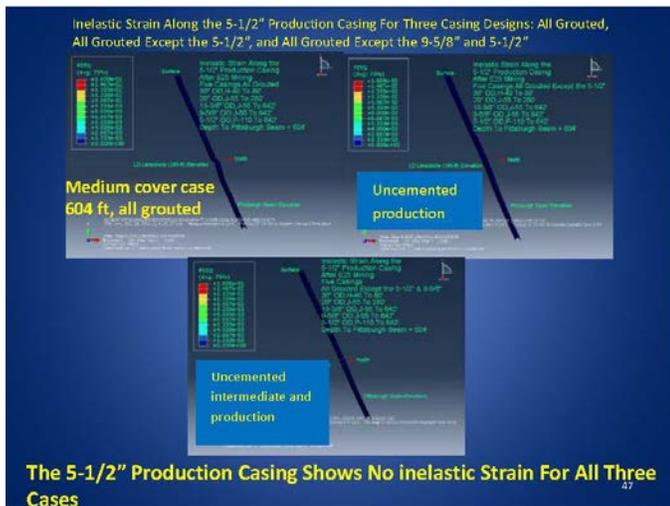


Figure 7B. Longwall-induced von Mises stress in the production casing at the medium cover site (604 feet).

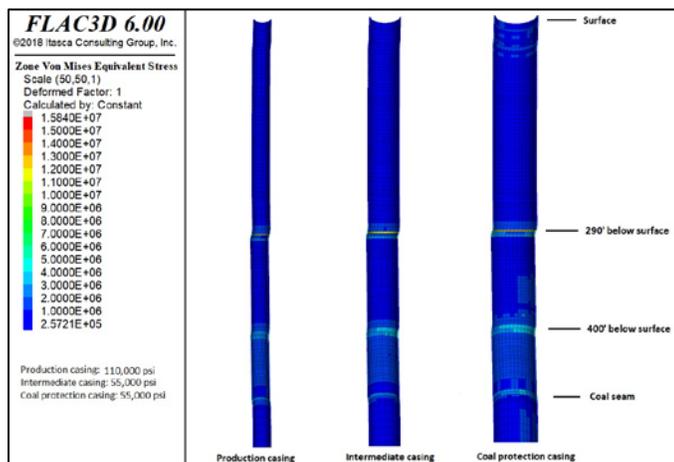


Figure 7C. Longwall-induced von Mises stress in the production casing (grouted to the surface) at the shallow cover site (482 feet).

Gas Well Setback Distance

The calibrated FLAC3D model was also used to evaluate the effect of gas well setback distance on longwall-induced von Mises

stress in the coal protection, intermediate, and production casings. Figure 8 shows the effect of setback distance on the induced von Mises stress in the production, intermediate, and coal protection casings of a hypothetical gas well drilled into a barrier pillar at a mining depth of 985 feet. This figure clearly indicates that when the projected longwall recovery line is at 100 feet from the gas well, the induced von Mises stress in the J-55 coal protection and J-55 intermediate casings are still below their rated yield strength of 55,000 psi, and the induced von Mises stress in the P-110 production casing is well below its rated yield strength of 110,000 psi. It is important to note that the setback distance is expected to be different under different overburden depth and geologic conditions. Figure 9 shows the effect of setback distance on the induced von Mises stress in the production casings of a hypothetical gas well drilled into a longwall abutment pillar, where the well is located at center of the chain pillar system. Modeling indicates that longwall-induced von Mises stress in the production casing increases with overburden depth and decreases with increasing setback distance. Figure 9 indicates that following the 1957 PADEP Gas Well Pillar Guidelines, J-55 casing yielding occurs when overburden depth is greater than 750 ft. However, longwall-induced von Mises stress in the P-110 unconventional gas well casing is 25% below its rated yield strength of 110,000 psi under 1000 feet of cover.

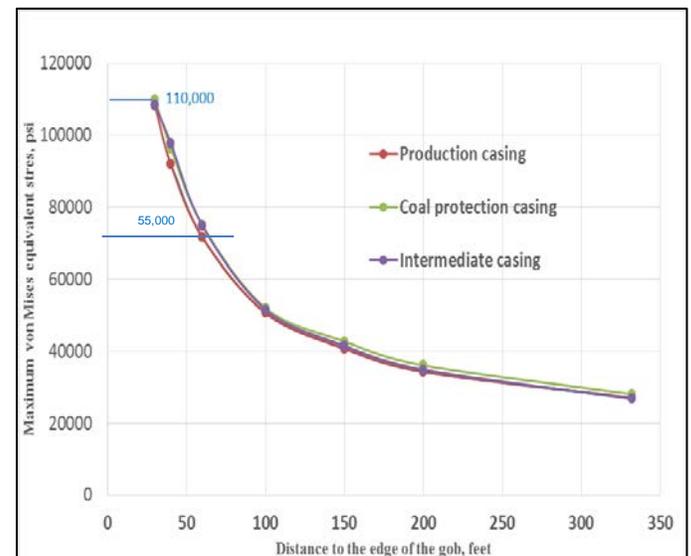


Figure 8. Maximum von Mises stress in the coal protection, intermediate, and protection casings versus distance to the projected longwall recovery line.

DISCUSSIONS

The field instrumentation as well as the numerical modeling results presented in this paper are consistent with a few previous attempts to characterize unconventional subsurface movements along the bedding planes (Su, 1991; Su, 2016; Su, 2018; Su, et al., 2018a and 2018b). Since about 1,500 unconventional shale gas wells have been drilled recently ahead of mining in the Pittsburgh coalfield and because nearly all casings of these wells are fully cemented to the surface, depending on the distance to the edge of future longwall extraction, potential casing deformation may be present. However, in all three case studies presented in this paper, the longwall-induced von Mises stress in the production casing stays below its rated yield strength.

It is important to note that longwall-induced von Mises stress in the casings depends not only on the longwall-induced lateral displacement, but also on the longwall-induced vertical compression or abutment pressure. Therefore, potential casing compromise is more likely to be present under very shallow cover with saturated overburden rocks where the longwall-induced lateral displacement is large, or under deep cover where the longwall-induced vertical compression is very high.

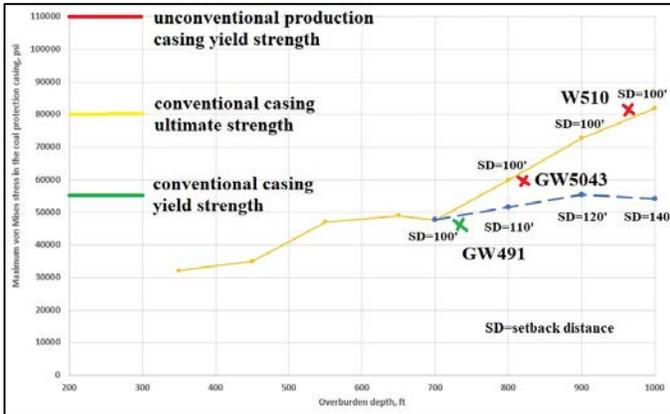


Figure 9. Maximum von Mises stress in production casings versus the setback distance.

CONCLUSIONS

This paper confirms that under shallow and medium covers, longwall-induced subsurface deformations are one order of magnitude higher than those observed under deep cover. On the other hand, longwall-induced vertical compressions under deep cover are one order of magnitude higher than those under shallow and medium covers. However, in all three case studies presented in this paper, the longwall-induced von Mises stress in the production casing stays below its rated yield strength. These findings are expected to have certain impact on coal operators' longwall pillar design decision. Modeling results indicate that stable production casing for unconventional gas wells meeting the 1957 PADEP guidelines. Leaving intermediate and/or production casings uncemented from 50 feet below the coal seam to surface would effectively uncouple the casings from longwall-induced ground movements. A gas well's setback distance, where the longwall-induced von Mises stress in the production, intermediate, and coal protection casings are below their rated yield strengths, is dependent on the overburden depth and geology and can be assessed on a site-specific basis.

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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