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NIOSH GAS WELL STABILITY RESEARCH – STATUS AND SIGNIFICANT FINDINGS

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ABSTRACT

To provide critical scientific data and engineering guidelines to federal and state regulatory agencies as well as the coal and gas industries, the National Institute for Occupational Safety and Health (NIOSH) initiated a Gas Well Stability Research Program in 2016. This paper summarizes the critical scientific data acquisition, interpretation, and modeling by NIOSH regarding the stability of unconventional shale gas wells influenced by longwall mining. Currently, NIOSH is the only organization in the U.S. conducting such fundamental and impact-oriented research, which receives input and collaborations from MSHA, PADEP, WVDMS, OHDNR, the coal industry, and the gas industry. Results from the NIOSH field instrumentation programs—which include surface, subsurface, and underground instrumentation—and the parallel three-dimensional numerical modeling programs 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. Casing couplers are found to play an important role in longwall-induced casing deformations. Cementing alternatives are found to have significant impact on longwall-induced casing stresses and deformations. Measured 60-arm caliper logging results are in good agreement with three-dimensional computer simulation results. Engineering guidelines on longwall-induced deformations, casing and cementing alternatives, gas well setback distances, as well as risk assessment strategy are proposed.

INTRODUCTION

Since 2003, over 1,500 unconventional shale gas wells have been drilled through active and future Pittsburgh Seam coal reserves in Pennsylvania, West Virginia, and Ohio. These unconventional gas wells, whether tapped into the Marcellus or Utica formations, contain very high gas pressure and volume. Strata deformations associated with underground longwall coal mining could induce 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 to 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 Mine Safety (WVDMS), the Ohio Department of Natural Resources (OHDNR), coal operators, and gas operators, NIOSH initiated a research program 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 and comparisons with a previous study by the coal and gas industries under medium 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), 2020 (Su et al., 2020; Zhang et al., 2020), and 2021 (Su and Zhang, 2021, Su et al., 2021, Zhang et al., 2021). This paper describes the status of the ongoing NIOSH Gas Well Stability Research and summarizes all significant findings on longwall-induced subsurface deformations and stresses and longwall-induced casing stresses under a variety of overburden depths and geology. Engineering guidelines on longwall-induced deformations and stresses, casing and cementing alternatives, gas well setback distances under chain pillar and barrier pillar scenarios, and risk assessment strategies are presented.

COMPARISONS OF GEOTECHNICAL INSTRUMENTATION AND FLAC3D SIMULATION RESULTS
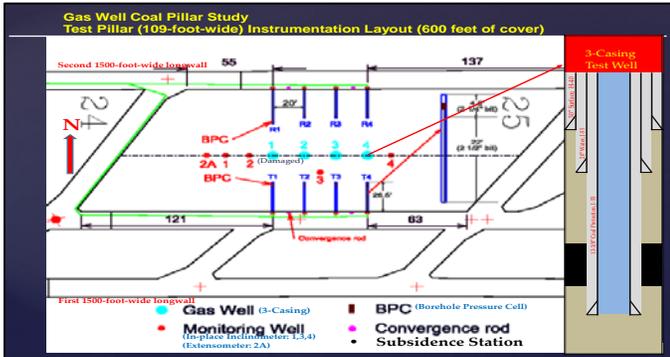
Test Site Instrumentation

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), the NV35 test site, 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, the 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.
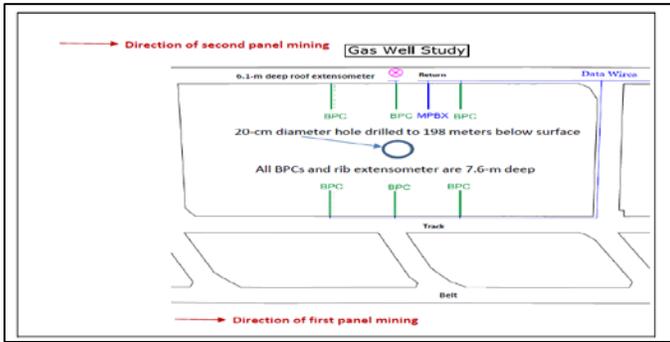
Deep Cover Test Site

Medium Cover (NV35) Test Site
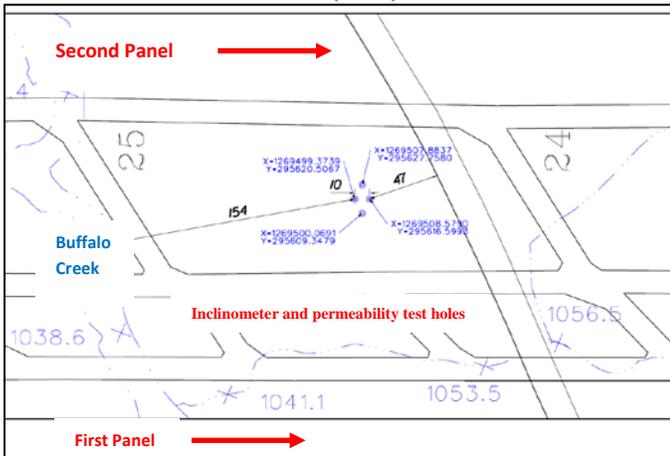
Shallow Cover Test Site

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

Test 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-, and 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.

FLAC3D Modeling and Comparisons with Field Instrumentation Results

While field instrumentation data were being collected, a suite of FLAC3D finite difference simulations (Itasca, 2017) were constructed

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 hypoelastic 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.

Comparisons of measured and calculated surface subsidence profiles, subsurface deformations, and underground pillar pressure increases at the three test sites were discussed and published previously (Su et al., 2019a and 2019b; Su et al., 2020a and 2020b; Zhang et al., 2020; Su and Zhang, 2021; Su et al., 2021; Zhang, et al., 2021). Table 1 summarizes the effects of cover depth on longwall-induced maximum subsurface lateral deformations and vertical abutment pressures.

Table 1. Measured longwall-induced maximum subsurface lateral deformation and vertical abutment pressure versus depth of cover.

Depth of cover, Meters (feet)	Maximum subsurface lateral deformations, mm (inches)	Maximum vertical abutment pressure, MPa (psi)
361 m (1,185 ft)	19 mm (0.75 in)	17.2 MPa (2494 psi)
184 m (604 ft)	108 mm (4.25 in)	2.6 MPa (400 psi)
147 m (482 ft)	168 mm (6.6 in)	0.7 MPa (102 psi)

EFFECT OF STRATA DIP ON LONGWALL-INDUCED HORIZONTAL DISPLACEMENTS

Coal seam dip is often neglected in modeling near-flat seams but cannot be ignored in modeling gas well stability in longwall chain pillars. The Pittsburgh Coal Seam and its overlying strata are not completely flat and often undulate gently or even dip slightly around geological structures like synclines or anticlines. In some areas, the seam dip angle can be as high as five degrees, and even this small dip can strongly influence horizontal movements of the overburden above chain pillars. Overburden dip creates a lateral force along the dip direction during the process of subsurface movements, which can either aid or resist horizontal movements in the overburden above chain pillars, depending on whether the overburden dips away from or towards the chain pillars. When the overburden dips away from the chain pillars, the lateral force helps the overburden strata to move away from the chain pillars, inducing more horizontal movements towards the longwall gob. Conversely, when the overburden dips towards the chain pillars, the lateral force resists the overburden strata from moving away from the chain pillars, which reduces the horizontal movements towards the gob.

To investigate how overburden dip can induce additional horizontal movements over the chain pillars, FLAC3D models with overburden dip angles from 0 to 5 degrees are constructed with NV35 test site geology and geometry, and the results are shown in Figure 2. When the overburden is flat, the maximum horizontal displacement is 4.5 cm at 119 m below the surface. With dip angle increasing from 0 to 5 degrees towards the gob, the maximum horizontal displacement at the same horizon increases to about 10 cm, which occurred after first-panel mining. This result suggests that a five-degree overburden dip can cause a 5.5-cm additional horizontal displacement. The additional horizontal displacement towards the dipping strata is approximately one centimeter for one degree of dip angle increase.

COMPARISON OF 60-ARM CALIPER LOGGING AND FLAC3D MODELING RESULTS

To understand longwall-induced casing deformations and to validate casing deformations predicted by numerical models, 60-arm Caliper logging results at the NV35 test site and at a 2020 test site are compared. Figure 3 shows the comparison of measured casing deformation as interpreted from a 60-arm caliper logging at the NV35

medium cover test site and the casing deformation predicted by finite element numerical modeling. The 2.2-inch deformation was detected at a limestone-to-coal interface, which coincided with the casing coupler location. Since at the coupler location, the upper and lower pipes typically had about a 1-inch gap, longwall-induced deformation tended to warp the upper or lower pipe to produce an apparent deformation.
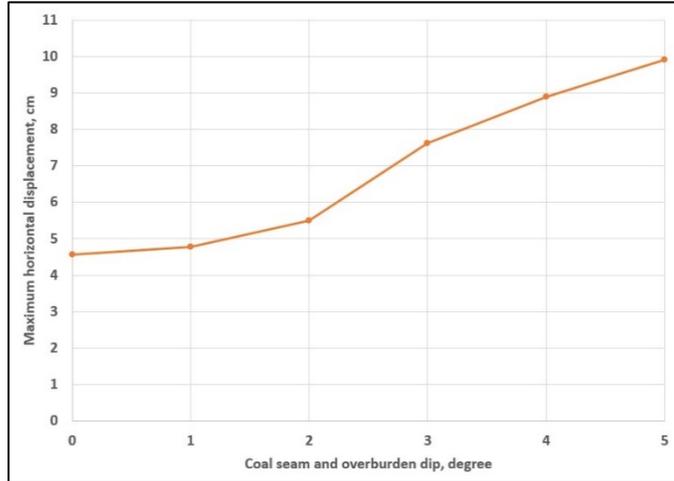

Figure 2. Effect of strata dip on longwall-induced subsurface horizontal displacements at the NV35 medium cover test site.
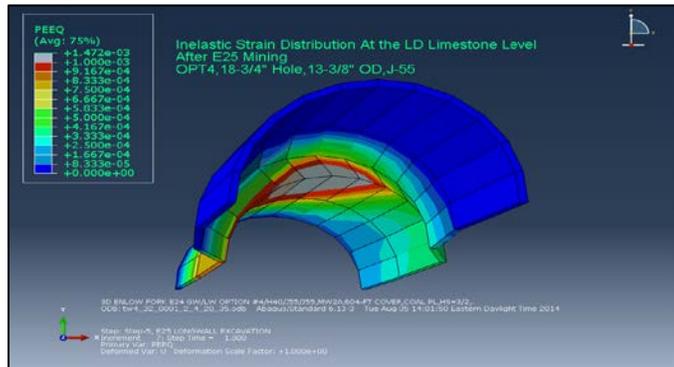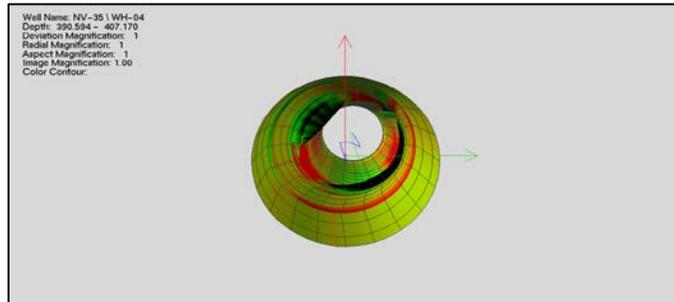

Figure 3. Comparison of measured and model-predicted casing deformation at the NV35 medium cover test site.

Figure 4 shows the excellent agreement between the measured and computed casing deformations at a 2020 test site, except for the measured deformation at the 168-ft depth level where a casing coupler was present. As explained above, the gap between the upper and lower pipes at the coupler tend to warp under longwall-induced shear deformation and create a larger apparent casing deformation (Figure 5).

FLAC3D MODELING OF GAS WELL CASINGS

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 6A, 6B, and 6C show that, in the three models 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 in the three modeled 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 model (Figure 6B) illustrates that leaving the intermediate and/or production casings uncemented from 50 feet below the coal seam to surface effectively uncouples the casing from longwall-induced ground movements.
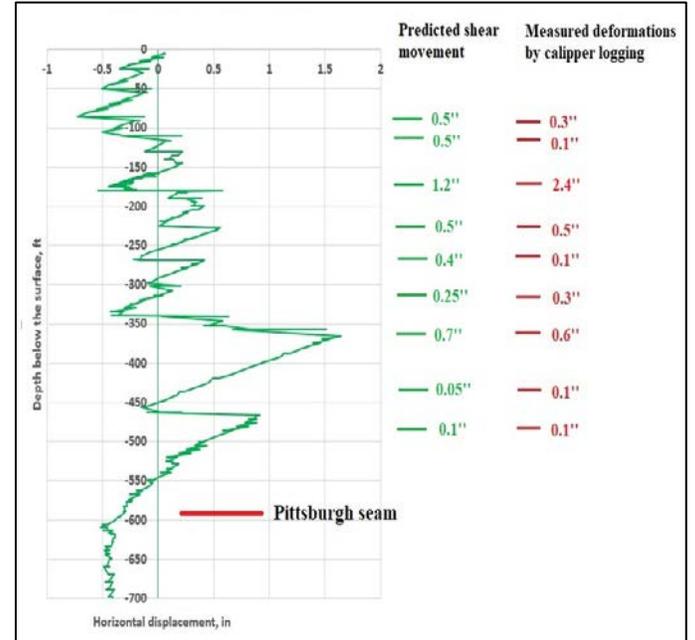

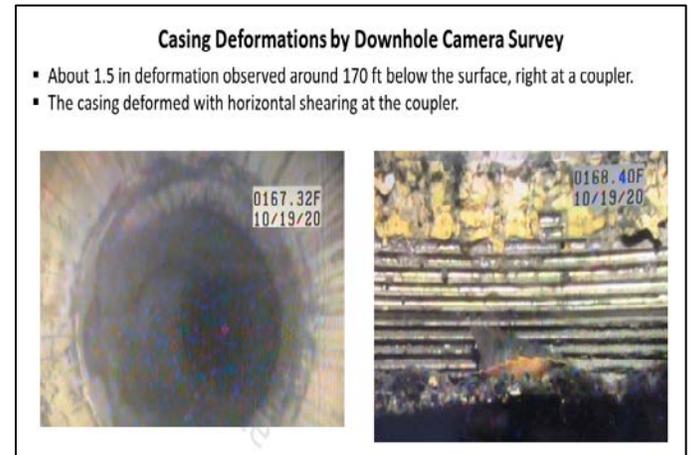**Figure 4.** Comparison of measured and model-predicted casing deformation at a 2020 test site.

Figure 5. Camera image at the 168-foot depth level where a casing coupler was present.

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 7 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 depths and geologic conditions.
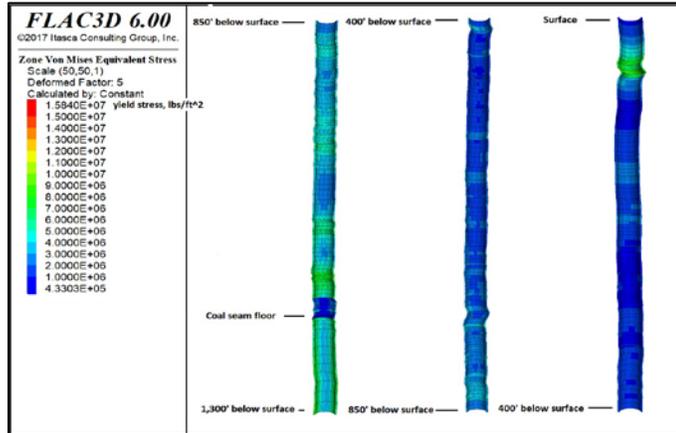

Figure 6A. Longwall-induced von Mises stress in the production casing of the deep-cover model.
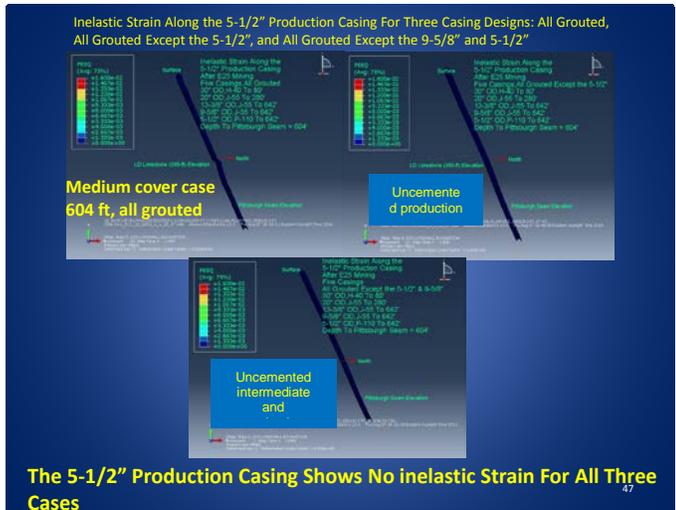

Figure 6B. Longwall-induced von Mises stress in the production casing of the medium cover model (604 feet).
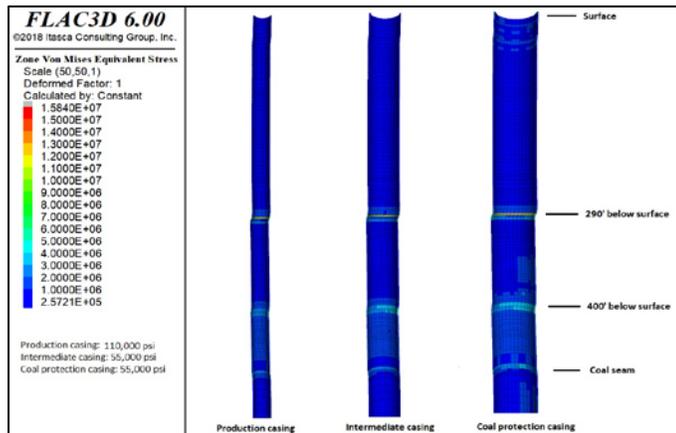

Figure 6C. Longwall-induced von Mises stress in the production casing of the shallow cover model (482 feet).
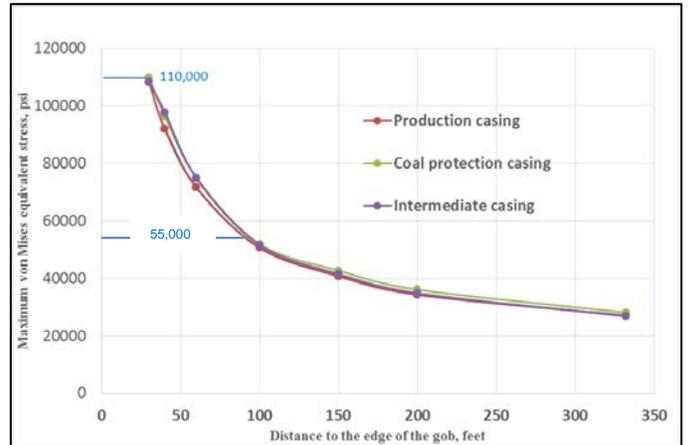

Figure 7. Maximum von Mises stress in the coal protection, intermediate, and protection casings versus distance to the projected longwall recovery line (barrier pillar scenario).

Figure 8 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 the center of the chain pillar system. Modeling results indicate that longwall-induced von Mises stress in the production casing increases with overburden depth and decreases with increasing setback distance. Figure 8 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 1,000 feet of cover.
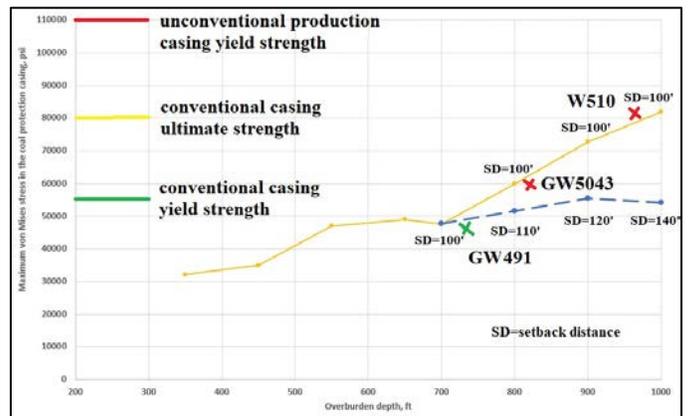

Figure 8. Maximum von Mises stress in production casings versus the setback distance (chain pillar scenario).

Significant Findings

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 longwall 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 extractions, potential casing deformation may be present. However, in all three case studies presented in this paper, the models predict that the longwall-induced von Mises stress in the production casing stays below its rated yield strength. It is important to note that the shallow cover case study was conducted to define the absolute worst-case scenario, which is not a realistic unconventional shale gas well scenario. The shallow cover test site was located only 60 feet from the center of a large stream valley and the entire overburden was saturated. Therefore, excluding the shallow cover

case, longwall-induced von Mises stress in the production casing is expected to stay below 80% of the P-110 casing's 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. However, longwall-induced lateral displacement is the much more dominant factor. Therefore, potential casing compromise is more likely to be present under shallow cover with saturated overburden rocks where the longwall-induced lateral displacement is large and less likely under deep cover.

Based on the field instrumentation and numerical modeling results available to date, a reasonable gas well risk assessment strategy needs to consider mining depth, overburden geology, surface topography, seam dip, gas well construction, and setback distance. Since most unconventional shale gas wells are drilled in areas where cover depth to the Pittsburgh Seam is more than 900 feet, the adequate setback distance is 100 feet under the barrier pillar scenario for the coal protection, intermediate, and production casings to stay below their respective API yield strengths. The adequate setback distance is more complex under the chain pillar scenario (PADEP, 2017). Assuming that the gas well is located at the center of the chain pillar system, to keep the coal protection, intermediate, and production casings from reaching their respective API yield strengths, the total pillar dimensions need to increase with depth (Figure 8). As shown in Figure 6B, leaving the intermediate and production casings uncemented from 50 feet below the Pittsburgh Seam to the surface would effectively uncouple the casings from longwall-induced deformations and stresses. Therefore, adjustment of chain pillar dimension with depth may not be necessary.

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 modeled longwall-induced von Mises stress in the production casing stays below the casing's rated yield strength. Leaving intermediate and/or production casings uncemented from 50 feet below the coal seam to the 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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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