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Longwall-induced shale gas well casing deformations and stresses-critical effects of geologic and geometric parameters

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ABSTRACT: This paper summarizes geo-mechanical findings from the ongoing Gas Well Stability research at the National Institute for Occupational Safety and Health (NIOSH)-in particular, the critical effects of geologic and geometric parameters on longwall-induced gas well casing deformations and stresses. Overburden geology is one of the most important factors affecting the longwall-induced casing deformations and stresses. The large contrast of bending stiffness at the soft-to-hard rock interfaces has been found to induce large casing deformations and stresses. Overburden depth to the mining seam is also an influential factor. Shallow overburden depth induces large horizontal displacement and resulting casing deformation and stress, due to smaller longwall-induced vertical pressure. Deep overburden depth induces large longwall-induced vertical pressure, which tends to limit longwall-induced horizontal movement. Strata dip would magnify longwall-induced deformations by 20% for each degree of strata dip with down dip longwall excavation. The gas well setback distance is a critical geometric parameter. The effect of longwall-induced deformation decreases exponentially as the setback distance increases. Longwall-induced casing deformation and stress will be mitigated or totally uncoupled if the production casing is uncemented. Longwall-induced fracture zone height is linearly propositional to the panel width.

1.INTRODUCTION

Over 2,000 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 casing. Damaged production casing 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, Pennsylvania Department of Environmental Protection, West Virginia Department of Mine Safety and Training, Ohio Department of Natural Resources, coal operators, and gas operators, NIOSH initiated a gas well stability research program in 2016 to evaluate the effects of longwall-induced deformations on shale gas well casing integrity under deep, medium, and shallow covers. This paper summaries important findings from the ongoing NIOSH Gas Well Stability research; in particular, the important geo-mechanical research findings on overburden geology, overburden depth, strata dip, gas well setback distance, gas well casing cementing alternative, and longwall-induced fracture zone.

2.GEOTECHNICAL INSTRUMENTATION AND FLAC3D SIMULATIONS

Detailed geotechnical instrumentations were conducted at six sites: two deep cover, two medium cover, and two shallow cover sites. At the six test sites, in addition to the surface subsidence and underground coal pillar pressure measurements, subsurface inclinometer and 60-Arm Caliper measurements were conducted to evaluate longwall-induced subsurface deformation. Detailed overburden geology down to the coal seam level were compiled by correlating available gamma logs and nearby core holes. Overburden geology above the Pittsburgh Seam contains many soft-to-hard 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. While field instrumentation data were being collected, a suite of FLAC3D finite difference simulations 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 site, was the primary model input. Specifically, over 120 weak-to-strong rock interfaces were present and simulated in each of the six 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 displacement, and measured underground coal pillar pressure increase.

3.EFFECTS OF OVERBURDEN GEOLOGY

Figure 1 shows the correlation of overburden geology and measured post-mining gas well casing deformation locations. Clearly, overburden geology is an influential factor affecting the longwall-induced casing deformations and stresses. Sharp contrast of bending stiffness at the soft-to-hard rock interfaces, such as coal/limestone, coal/sandstone, claystone/limestone, and claystone/sandstone interfaces, is demonstrated to induce post-mining casing deformations and stresses. A large contrast of bending stiffness at the soft-to-hard rock interfaces, such as a thin coal/claystone layer overlaid or underlaid by a thick limestone/sandstone layer, is expected to induce large post-mining subsurface and casing deformations.

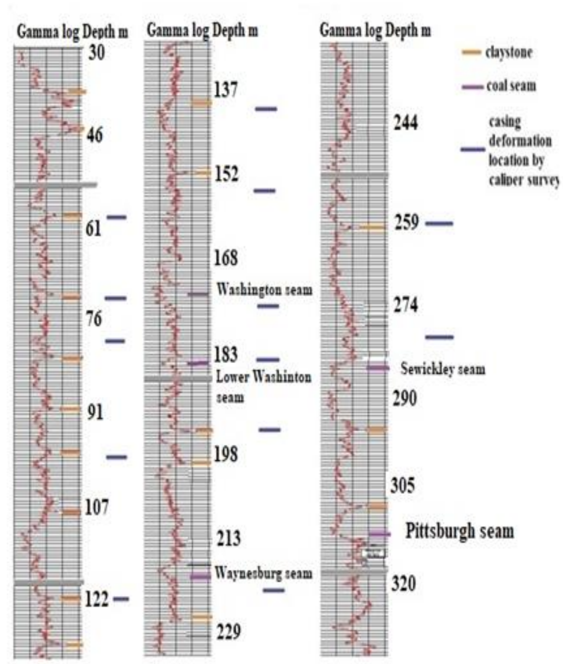

Figure 1. Correlation between presence of soft-to-hard rock interfaces and post-mining measured casing deformation locations.

4.EFFECTS OF OVERBURDEN DEPTH ON LONGWALL-INDUCED SUBSURFACE DEFORMATIONS AND ABUTMENT PRESSURES

Table 1 summarizes the effects of cover depth on longwall-induced maximum subsurface lateral deformations and vertical abutment pressure at the six test sites, which indicate that overburden depth to the mining seam is one of the most influential factors. Shallow overburden depth induces large horizontal displacement and resulting casing deformation and stress due to smaller longwall-induced vertical pressure. Deep overburden depth induces large longwall-induced vertical pressure, which tends to limit longwall-induced horizontal movement.

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)	Total vertical abutment pressure, MPa (psi)
361 m (1,185 ft)	19 mm (0.75 in)	26.3 MPa (3,810 psi)
314 m (1,030 ft)	13 mm (0.5 in)	10.9 MPa (1,580 psi)
184 m (604 ft)	108 mm (4.25 in)	10.5 MPa (1,523 psi)
177 m (580 ft)	38.1 mm (1.5 in)	9.79 MPa (1,420 psi)
168 m (550 ft)	43.2 mm (1.7 in)	9.34 MPa (1,355 psi)
147 m (482 ft)	168 mm (6.6 in)	4.36 MPa (632 psi)

However, large longwall-induced vertical pressure may induce unusually high casing stress, especially with near-seam sharp soft-to-hard rock interface, leading to large casing deformation for fully cemented production casing. A recent case study at a NIOSH industry cooperator's well site revealed an anomalous shale gas well casing deformation at a deep Pittsburgh Seam longwall mine. Figure 2 shows the location of a gas well pad over a longwall abutment pillar in a Pennsylvania coal mine with an overburden depth of 1,307 feet (398 meters). The longwall panel employed at this mine was 1,500-feet (457-m) wide, and the average mining height was 7 feet (2.13 m). The abutment pillar below the gas well pad was 134 feet (41 M) wide rib-to-rib. Five unconventional shale gas wells, where all casings were fully cemented to the surface, were drilled over the longwall gate-road in late 2010, although due to deviation, only three of the five wells were located inside the abutment pillar (Figure 3). At the request of NIOSH researchers, the gas operator purposely left the 4H well open for post-mining evaluation and plugged the remaining four wells. The first longwall panel, located on the north side of the well pad, mined past the well site in May 2022, and the second longwall panel, located on the south side of the well pad, mined past the well site in March 2023.

Prior to the collection of post-mining field measurements, a suite of FLAC3D finite difference simulations 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 data, compiled from a nearby core hole (>580 meters away) and from an on-site gamma log, was the primary model input. Prior to the first longwall excavation, overburden geology from the core hole 580 meters away was the primary input to the model. Upon detection of the plastic casing deformation at the 1,284-foot (392-m) horizon, an on-site gamma log was conducted, which revealed the presence of a thick claystone layer at 23 feet (7 m) above the Pittsburgh Seam. This thick claystone layer was not present in the core hole 580 meters away from the study well. As such, the FLAC3D model was reconstructed and rerun with the overburden geology obtained from the on-site gamma log. The primary goal of the simulations was to duplicate measured surface subsidence and measured casing diameter changes by the 40-Arm Caliper surveys. Figure 4 illustrates the longwall-induced pillar pressure at the deep-cover test site, which shows an average pillar pressure of more than 3,000 psi (20.7 MPa) at the gas well location and which is expected to impact the longwall-induced casing stresses.

Post-first and post-second panel mining 40-Arm Caliper and camera surveys were conducted in the test well, 4H, which revealed a large plastic casing deformation at the 1,284-foot (392-m) depth horizon (Figure 5). A few FLAC3D models were subsequently constructed to investigate the causes of plastic casing deformation at the 1,284-foot (392-m) horizon. Figure 6 shows the longwall-induced casing stress at the deep-cover study site, where the depth to the Pittsburgh seam is 1,307 feet (398 meters). Figure 6 only shows the high stress portion of the casing, which is located near the thick claystone horizon 23 feet (7 meters) above the Pittsburgh Seam. Clearly, this longwall-induced casing stress exceeds the rated yield strength of the P-110 casing and substantial plastic casing deformation occurs, which helps to explain the plastic casing deformation observed by the downhole camera at the claystone horizon 23 feet (7 meters) above the Pittsburgh Seam. To investigate under what cover depth this type of plastic casing deformation may occur, three additional FLAC3D models were constructed and analyzed. Figure 7 shows that, under a cover depth of 1,000 feet (305 meters) or less, longwall-induced deformations in fully cemented production casing are expected to stay in the elastic range. On the other hand, Figure 7 also indicates that strain hardening in fully cemented production casing is likely for cover depths up to 1,200 feet (366 meters) and plastic casing deformation is likely for cover depths greater than 1,200 feet (366 meters).

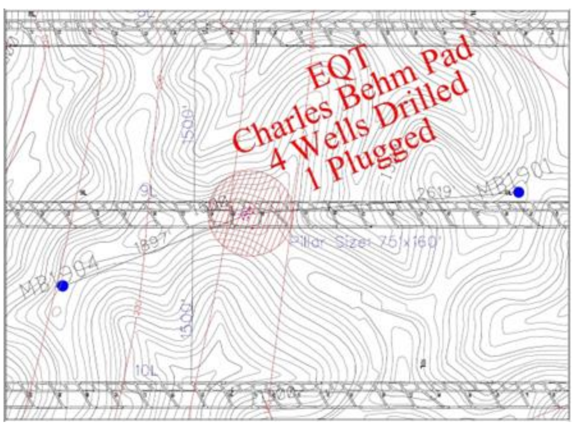

Figure 2. Location of a gas well pad over the longwall abutment pillar in a deep mine.

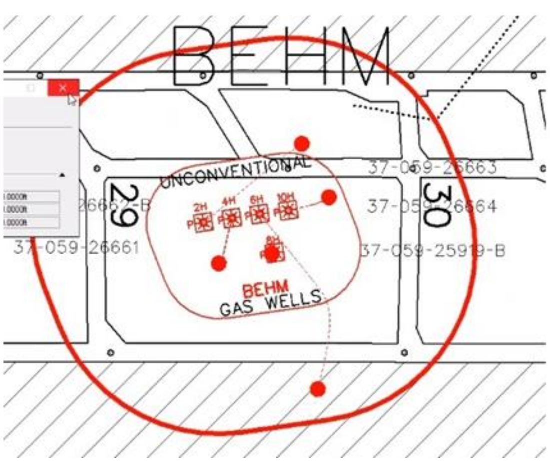

Figure 3. Actual gas well location at the Pittsburgh Seam horizon versus the surface location due to well deviation.

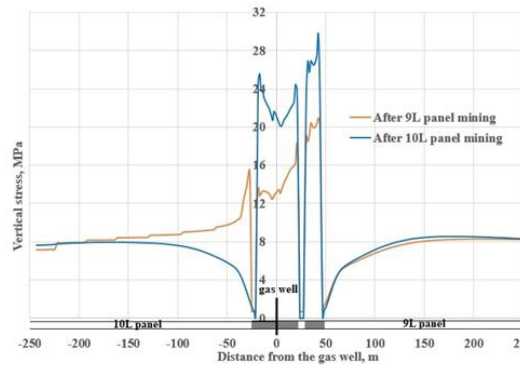

Figure 4. Longwall-induced vertical pillar pressure at the deep-cover test site.

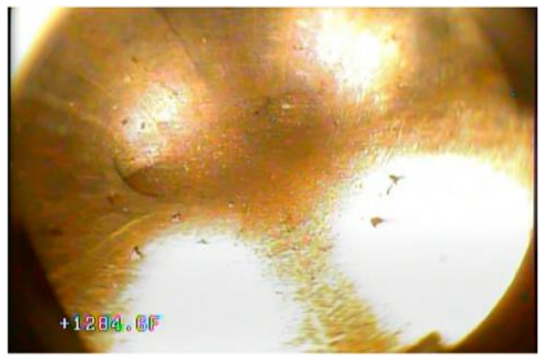

Figure 5. Large casing deformation at the 1,284-foot (392-m) depth horizon detected by the 40-Arm Caliper and camera surveys.

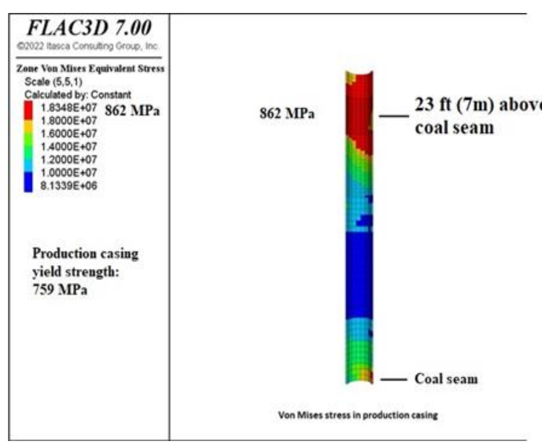

Figure 6. Longwall-induced production casing stress near the thick claystone horizon at the deep-cover study site (398-meter cover depth).

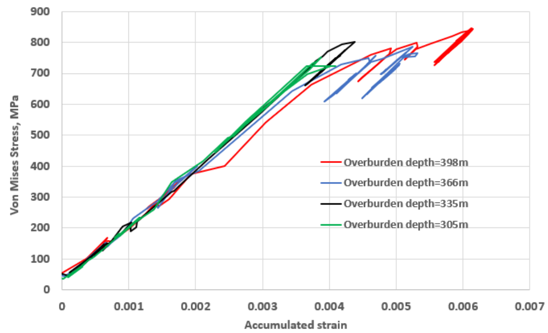

Figure 7. Effect of cover depth on longwall-induced casing stress and plastic casing deformation.

5.EFFECTS OF STRATA DIP ON LONGWALL-INDUCED SUBSURFACE DEFORMATIONS

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 the medium-cover test site geology and geometry, and the results are shown in Figure 8. When the overburden is flat, the maximum horizontal displacement is 4.5 cm (1.77 inches) at 119 m (390 feet) 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 (3.94 inches), which occurred after first-panel mining. This result suggests that a five-degree overburden dip can cause a 5.5 cm (2.17 inches) additional horizontal displacement. The additional horizontal displacement towards the dipping strata is approximately one centimeter (0.39 inch) for one degree of dip angle increase.

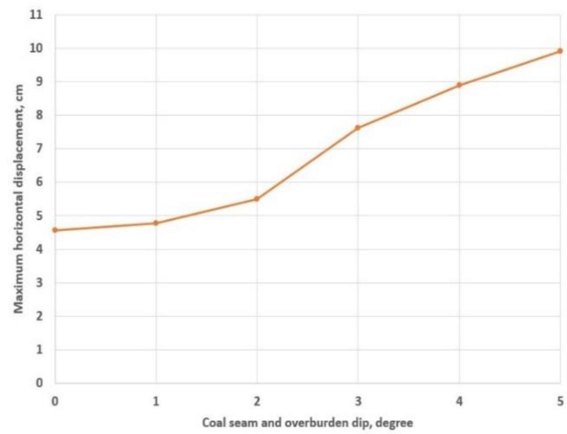

Figure 8. Effect of strata dip on longwall-induced subsurface horizontal displacement at the medium cover (NV35) test site.

6.EFFECTS OF 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 9 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 300 meters (984 feet). This figure clearly indicates that when the projected longwall recovery line is at 30 meters (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 379 MPa (55,000 psi), and the induced von Mises stress in the P-110 production casing is well below its rated yield strength of 759 MPa (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 10 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 indicates that longwall-induced von Mises stress in the production casing increases with overburden depth and decreases with increasing setback distance. Figure 10 indicates that following the 1957 PADEP Gas Well Pillar Guidelines, J-55 casing yielding occurs when overburden depth is greater than 228 meters (750 feet). However, longwall-induced von Mises stress in the P-110 unconventional gas well casing is 25% below its rated yield strength of 759 MPa (110,000 psi) under 300 meters (1,000 feet) of cover.

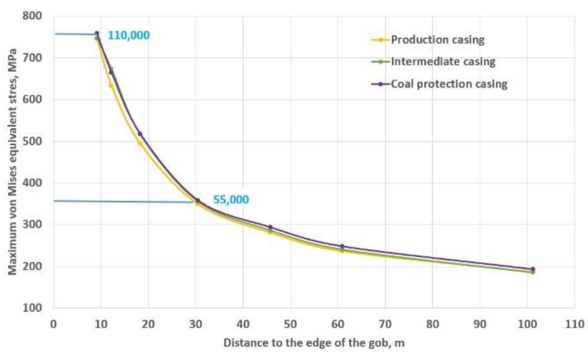

Figure 9. Maximum von Mises stress in the coal protection, intermediate, and protection casings versus distance to the projected longwall recovery line (barrier pillar scenario).

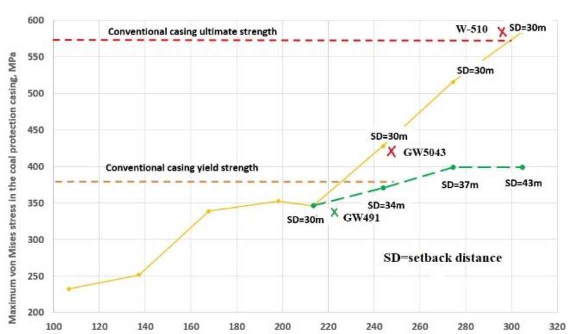

Figure 10. Maximum von Mises stress in production casings versus the setback distance (chain pillar scenario).

7.EFFECTS OF CASING CEMENTING ALTERNATIVES ON LONGWALL-INDUCED CASING DEFORMATIONS AND STRESSES

Figure 11 shows the effect of leaving the production casing uncemented. Since the annular space between the 9-5/8" (24.4 cm) intermediate casing and the 5-1/2" (14 cm) production casing is 3.365 inches (8.55 cm), post-mining longwall-induced casing deformations smaller than 3.365 inches (8.55 cm) are not expected to cause any production casing deformation. In other words, leaving the production casing uncemented has very high probability of uncoupling longwall-induced deformations from the production casing.

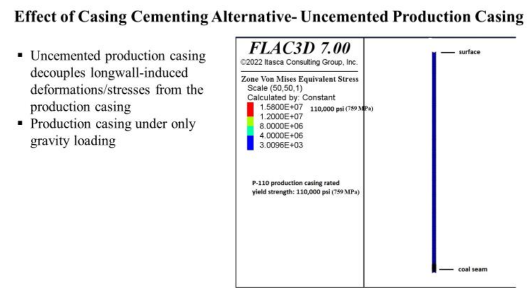

Figure 11. Longwall-induced casing stress in an uncemented production casing.

8.LONGWALL-INDUCED FRACTURE ZONE

To understand the extent of overburden fractures after longwall mining, NIOSH researchers drilled pre-mining and post-mining core holes into a Pittsburgh Coal Seam longwall gob (Van Dyke et al., 2022). Knowing the extent of the fracture zone height will help gas operators minimize the hazards of drilling into longwall gobs. Rock cores (Figure 12) were retrieved from the surface down to the top of the gob void. Various fractures were encountered varying from 35 to 64 degrees depending on lithologic type and relative closeness to the gob. The longwall panel dimension was 1,500-ft (457-m) wide and 12,000-ft (3658-m) long in which the fracture zone height was found to be at 329 ft (100 meters) above the top of the Pittsburgh Seam. In addition to core drilling through the gob, FLAC3D modeling was also used to simulate the formation of fracture zone and the orientations of longwall-induced fractures, which indicates that the predicted post-mining fracture zone height to be 338 feet (103 meters) above the mine level (Figure 13). Combined with two previous studies by the coal industry, Figure 14 shows the longwall-induced fracture zone height versus the longwall panel width for the Pittsburgh Seam mining scenario, which indicates a nearly linear relationship between the longwall-induced fracture zone height and longwall panel width. This study provides much needed evidence on the fracture zone of Pittsburgh Seam longwall gobs to help gas operators avoid potential hazards associated with drilling through highly fractured zones in longwall gobs.

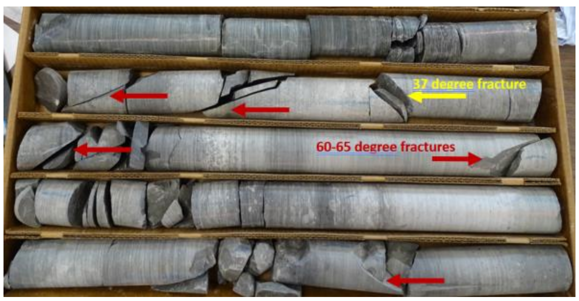

Figure 12. Retrieved post-mining rock core showing longwall-induced high angle fractures.

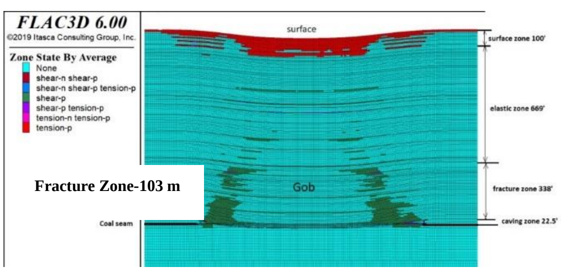

Figure 13. FLAC3D modeling of longwall-induced fracture zone above a 457-meter-wide longwall panel.

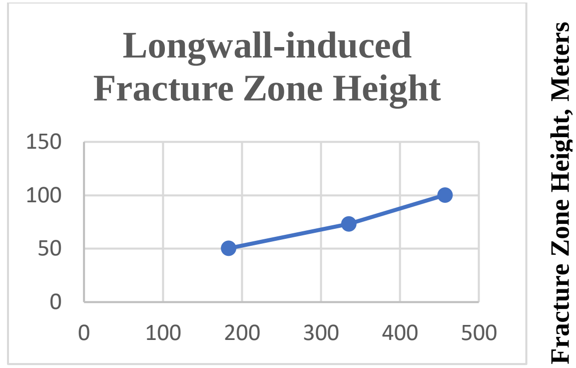

Figure 14. Longwall-induced fracture zone height versus longwall panel width.

9.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 over 2,000 unconventional shale gas wells have been drilled recently ahead of longwall mining in the Pittsburgh coalfield and the production casings in 80% 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. Fortunately, recent gas well installation practices have shifted to uncemented production casing.

10.CONCLUSIONS

This paper presents recent geo-mechanical findings from the current NIOSH gas well stability research. 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, strata dip, setback distance, gas well cementing alternatives, and longwall-induced fracture zone height. Recent research findings indicate 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. Overburden geology is another important factor affecting the longwall-induced casing deformations and stresses; a large contrast of bending stiffness at the soft-to-hard rock interfaces tends to induce large casing deformations and stresses.

Although often overlooked in a conventional longwall subsidence study, strata dip is found to have significant influence on the magnitudes of longwall-induced subsurface deformations. A strata dip of 1% could cause 20% more subsurface longwall-induced horizontal displacement, although its impact on actual gas well casing deformation is minimal. Cementing alternatives are found to have significant impacts on longwall-induced casing deformations and stresses. Uncemented production casing serves to significantly mitigate longwall-induced casing deformations and stresses. Longwall-induced fracture zone height is linearly proportional to the panel width.

11.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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