

Effects of Surface Topography, Strata Dip, and Casing Cementing on Longwall-induced Subsurface Deformations and Gas Well Casing Stresses

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ABSTRACT

This paper describes the scientific data acquisition, data interpretation, and sophisticated 3-dimensional modeling processes of an ongoing gas well stability research program by the National Institute for Occupational Safety and Health (NIOSH). Results from the NIOSH field instrumentation programs and the parallel 3-dimensional numerical modeling programs indicate that overburden depth, overburden geology, surface topographic relief, strata dip of the coal measure rocks, and casing cementing alternatives are the dominant factors affecting longwall-induced subsurface deformations and gas well casing stresses. Topographic relief could produce localized longwall-induced deformations if weak-to-strong rock interfaces are present near the bottom of stream valleys. Strata dip has significant impact on longwall-induced subsurface deformations. Cementing alternatives are found to have significant impacts on longwall-induced deformations and gas well casing stresses.

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 2017), 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, under medium cover, and under shallow cover were published previously (Su et al., 2018a and 2018b; Su et al., 2019a and 2019b; Su et al., 2020; Zhang et al., 2020; Su and Zhang, 2021; Su et al., 2021; Zhang et al., 2021). This paper focuses on a few recent findings from the ongoing NIOSH Gas Well Stability Research. The effects of surface topographic relief, strata dip, and cementing alternatives on longwall-induced subsurface deformations and gas well casing stresses are presented.

GEOTECHNICAL INSTRUMENTATION AND FLAC3D SIMULATIONS

Geotechnical Instrumentation

Detailed geotechnical instrumentations were conducted at six sites over the past seven years: two deep cover, two medium cover, and two shallow cover sites. However, since the focus of this paper is on the effects of surface topographic relief, strata dip, and casing cementing alternatives on longwall-induced subsurface deformations and casing stress, only two medium cover cases and one shallow cover case will be discussed in detail.

The first medium cover site, dubbed the NV35 test site, was 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 second medium cover site, a test site carried out by the coal and gas industries in 2020, was located over a West Virginia coal mine employing 1,200-foot-wide longwall panels to extract coal from the Pittsburgh Seam, which lies 580 feet below the surface. A three-entry gate-road system of 50-ft x 106-ft centers was employed at the mine.

The shallow cover site, a conventional well site, is located over a southwestern Pennsylvania coal mine employing 1,200-foot-wide panels to extract coal from the Pittsburgh Seam, which lies 550 feet below the surface. A three-entry longwall gate-road system of 100-ft x 100-ft centers was employed at the mine.

Test Site Geology

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 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

At the NV35 medium cover test site, three subsurface inclinometer monitoring holes were installed over the center of the 125-ft x 275-ft centers abutment pillar, eight borehole pressure cells were installed into the 125-ft x 275-ft centers abutment pillar, and pre- and post-mining surface subsidence surveys were conducted. In addition, four test wells were also installed. The test wells only had three casings, namely, surface, water, and coal protection casings. Pre-mining and post-mining 60-arm Caliper surveys were conducted in all four NV35 test wells. At the medium cover coal/gas industry test well site, surface subsidence survey, underground pillar pressure measurement, and pre- and post-mining 60-arm Caliper surveys were also conducted. At the shallow cover conventional well site, only pre- and post-mining 60-arm Caliper surveys were conducted. At this shallow cover conventional well site, the 7-inch production casing was not cemented from 1,400 feet below the surface to the surface.

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 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. 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 two medium cover sites and the NV35 test site 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 and Su, 2021).

EFFECTS OF SURFACE TOPOGRAPHIC RELIEF

Figures 1 and 2 show the surface layout and mine map overlay at the NV35 test site and the geo-mechanical instrumentation carried out at the test site. Figure 1 reveals that the surface topographic relief is approximately 360 feet from the hilltop test well location to the stream valley bottom of Ten Mile Creek. It is important to note that the NV35 test site is located at the crest of the Washington anticline and the strata dip 5 degrees southeastward towards the Nineveh syncline. Figure 3 shows the interpreted overburden geology above the Pittsburgh Seam at the NV35 test site from a test site E-log, which indicates the presence of a pronounced claystone/coal to limestone interface at 390 feet below the surface, which is approximately 30 feet below the stream valley bottom of the Ten Mile Creek. Figure 4 shows the measured subsurface test well casing deformations by 60-arm Caliper survey, which indicates the presence of the largest casing deformation and deviation at the 390-foot depth. This is consistent with a few previous observations of longwall-induced subsurface displacements in the vicinity of stream valley bottoms, provided that a distinct strong-to-soft rock interface is present in the vicinity of the stream valley bottoms. Note that the 4.25-inch horizontal displacement shown in Figure 4 is not the casing deformation; rather, it is the longwall-induced casing profile displacement. The actual casing deformation at the 390-foot depth is only 2.3 inches.

Figures 5, 6, 7, and 8 show test well and mine map overlay at a medium cover coal/gas industry test well site, test site geology from the test site E-log, test site surface topographic relief, and comparison of measured and computed subsurface deformations. Figure 7 indicates that there is a topographic relief of approximately 150 feet from the test well site to the stream valley bottom. Figure 6 indicates that a weak claystone layer is present below the stream valley bottom, which also shows the locations and magnitudes of measured subsurface casing deformations from a 60-arm Caliper survey. Figures 6 and 8 clearly show that the maximum casing deformation occurs at the weak claystone horizon

168 feet below the surface, which is about 18 feet below the stream valley bottom.

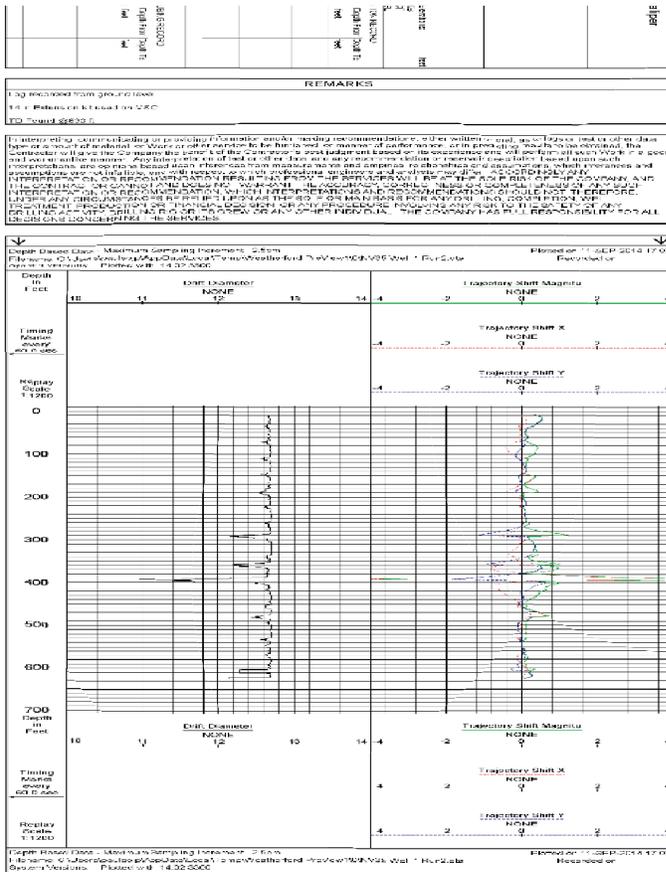
EFFECTS OF STRATA DIP ON LONGWALL-INDUCED SUBSURFACE DEFORMATIONS

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 NV35 test site geology and geometry, and the results are shown in Figure 9. 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.

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

Figures 10 and 11 show well pad and mine map overlay at a shallow cover conventional well site and a comparison of measured and computed subsurface



Result of 60-Arm Caliper Log After First Panel Mining

Maximum deformation at the 390-foot depth horizon = 4.25 inches

Figure 4. Measured test well deformations from 60-arm Caliper survey at the NV35 test site.

Test Site

- The test well is located at the center of Panel 17 abutment pillar
- Pillar design at the test well site: 106 × 275 ft, and 50 × 137.5 ft (center-to-center)
- Test well pillar width: 90 ft (rib-to-rib)
- Closest distance from the gas wells to the edge of Panel 18 gob: 45 ft
- Panel width: 1,216 ft (center-to-center)
- Overburden depth at the test well site: 580 ft
- Average mining height: 84 inches

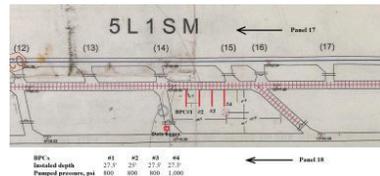


Figure 5. Test well and mine map overlay at a coal/gas medium cover site.

Comparison of Geology and Casing Deformations after Panel 18 Mining

- Casing deformations occurred at strong/weak rock interfaces.
- Deformations were measured and predicted at 9 strong/weak rock interfaces above the Pittsburgh seam for both first and second panel mining.

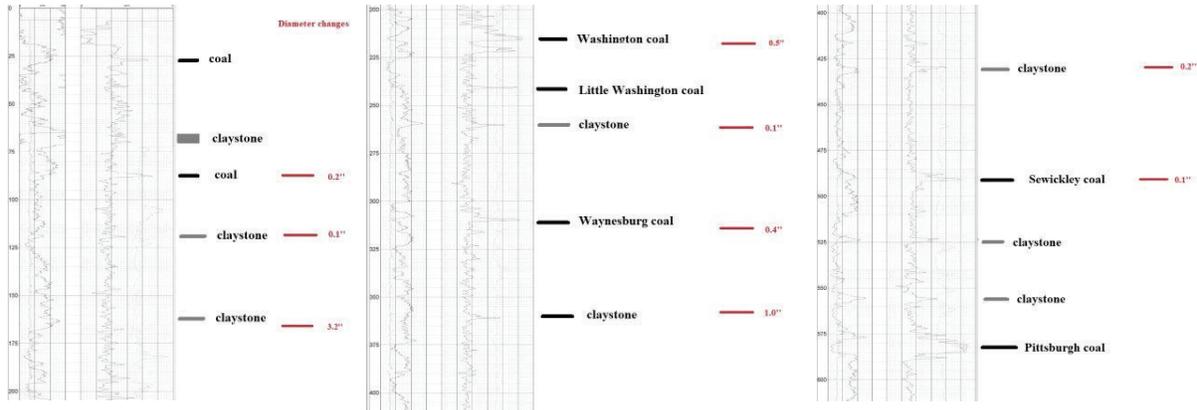


Figure 6. Comparison of geology and casing deformation after second-panel mining.

Surface Features

- Surface elevation was modeled in FLAC3D
- A creek is present about 500 ft on the south -east side

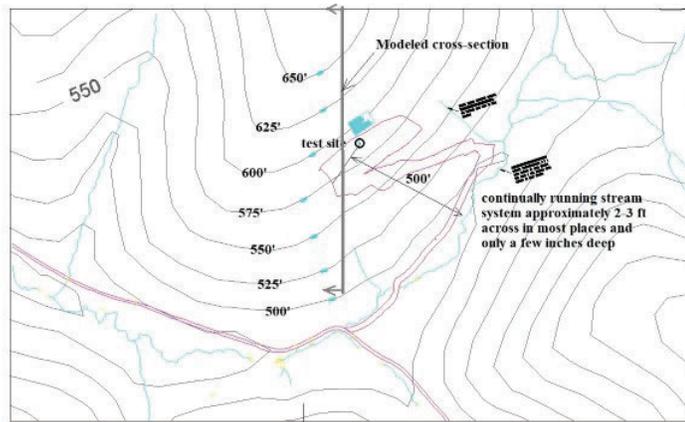


Figure 7. Surface topographic relief at the coal/gas medium cover test well site.

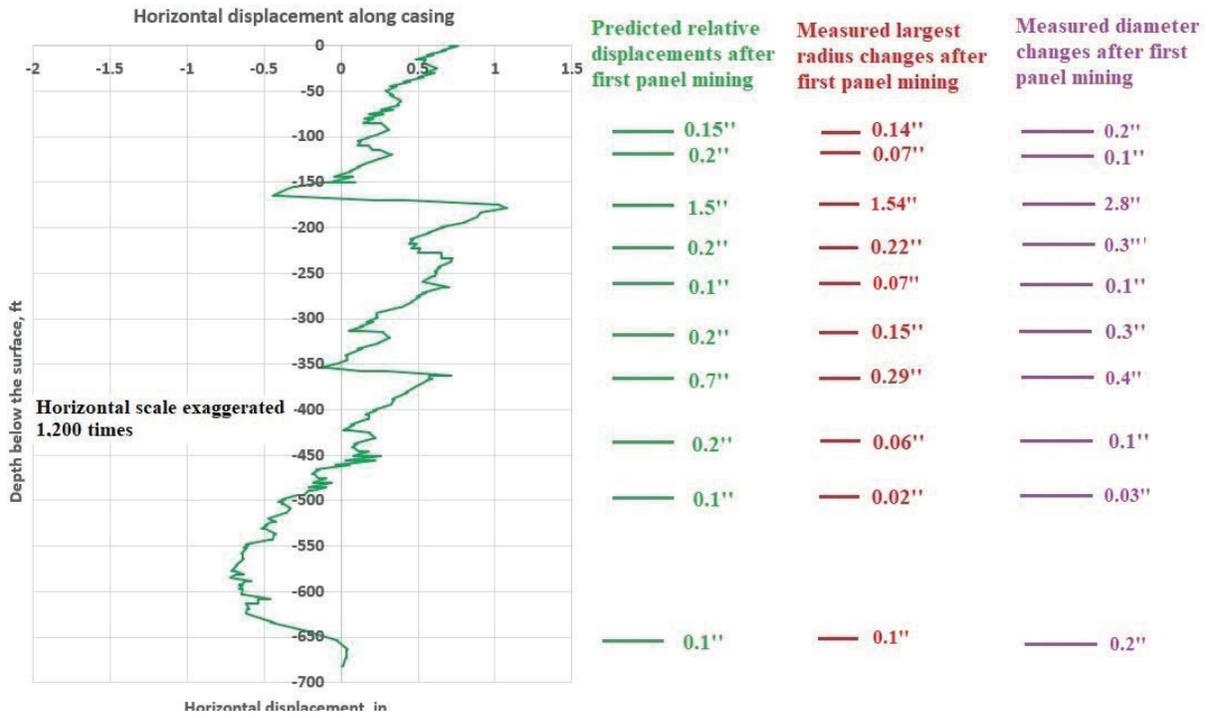


Figure 8. Measured and computed subsurface deformations at the medium cover coal/gas industry test well site.

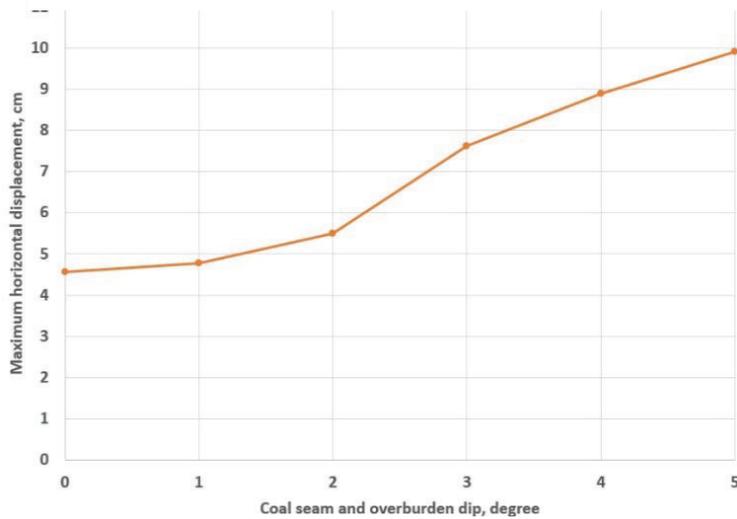


Figure 9. Effect of strata dip on longwall-induced subsurface horizontal displacements at the NV35 test site.

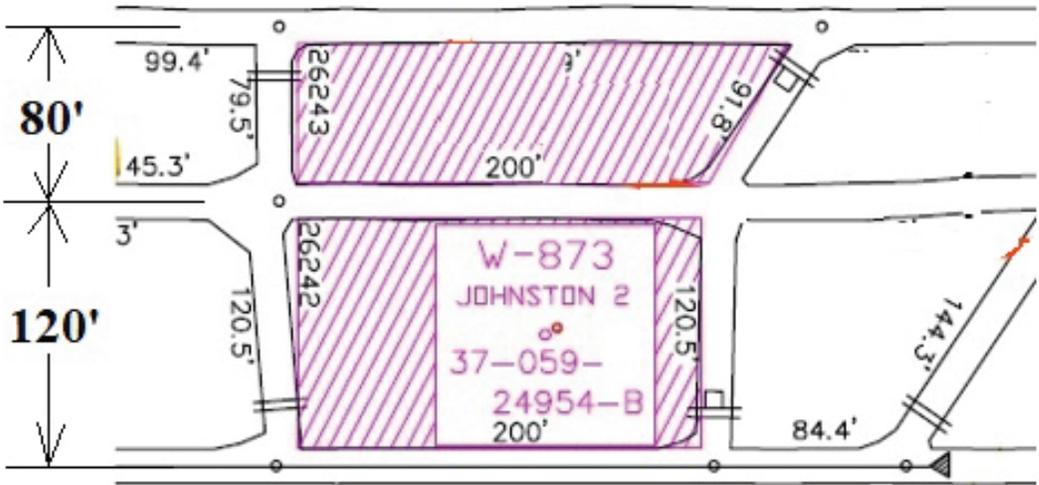
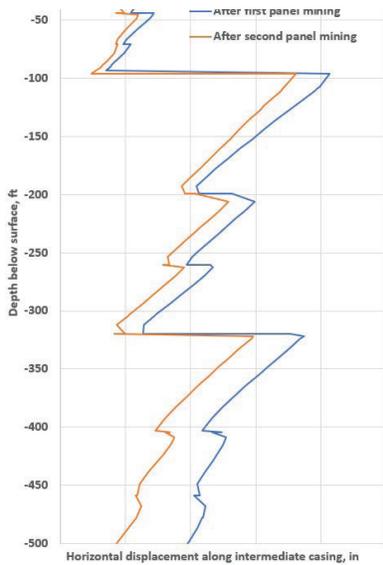


Figure 10. Conventional well location at a shallow cover site.



Comparison between Predicted and Measured Deformations						
Depth below surface, ft	Predicted relative displacement along intermediate casing after first panel mining, in	Predicted accumulated relative displacement along intermediate casing after second panel mining, in	Estimated production casing deformation after first panel mining, in	Actual production casing deformation after first panel mining, in	Estimated production casing deformation after second panel mining, in	Actual production casing deformation after second panel mining, in
95	1.7	1.85	0.26	0	0.47	0.4
205	0.2	0.3	0	0	0	0
260	0.15	0.2	0	0	0	0
320	1.3	1.60	0	0.1	0.12	0.2

Figure 11. Measured and computed subsurface deformations at the shallow cover conventional well site.

FINDINGS AND 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 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.

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. 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.

Although often overlooked in traditional longwall subsidence study, surface topographic relief and strata dip are found to have significant influence on not only the locations, but also on the magnitudes of longwall-induced subsurface deformations. Depending on the surface topographic relief and presence of soft-to-strong rock interfaces below the stream valley bottoms, maximum longwall-induced subsurface deformations in gas well casings could be close to the surface, thus having less impact on underground mining operations. A coal seam dip of 1% could cause 20% more subsurface longwall-induced horizontal displacement, although at the majority of unconventional shale gas well sites, the Pittsburgh Seam is nearly flat.

CONCLUSIONS

This paper presents a few recent findings from the current NIOSH gas well stability research. Surface topographic relief is found to produce localized longwall-induced deformations, which tends to shift the maximum longwall-induced deformations closer to the surface, if weak-to-strong rock interfaces are present near the bottom of stream valleys. Strata dip has significant impact on longwall-induced subsurface deformations, 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.

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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