# NIOSH Gas Well Stability Research: A Summary of Ground Control Engineering Considerations

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**ABSTRACT**

This paper summarizes significant findings from the ongoing NIOSH Gas Well Stability research over the past decade; in particular, the important ground control engineering considerations. Longwall-induced surface and subsurface deformations may induce gas well casing deformations and stresses, depending on a few parameters such as overburden depth, overburden geology, topographic relief, strata dip, gas well setback distance, and a gas well casing cementing alternative. 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, while deep overburden depth induces large longwall-induced vertical pressure. Overburden geology is another important factor affecting the longwall-induced casing deformations and stresses; the large contrast of bending stiffness at the soft-to-hard rock interfaces tends to induce large casing deformations and stresses. Large surface topographic relief and the presence of soft-to-hard rock interfaces below the stream valley bottoms may shift longwall-induced subsurface gas well casing deformations closer to the surface, thus having less impact on underground mining operations. Strata dip magnifies longwall-induced deformations by 20% per degree of strata dip for down dip longwall excavations. The gas well setback distance is also 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 for uncemented production casing.

## INTRODUCTION

Since 2003, 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, 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 and Training (WVDOMST), the Ohio Department of Natural Resources (OHDNR), coal operators, and gas operators, the National Institute for Occupational Safety and Health (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 and Su, 2021; Su et al., 2023). This paper summaries significant findings from the ongoing NIOSH Gas Well Stability research over the past decade; in particular, the important ground control engineering considerations on overburden depth, overburden geology, topographic relief, strata dip, gas well setback distance, and gas well casing cementing alternative.

## GEOTECHNICAL INSTRUMENTATION AND FLAC3D SIMULATIONS

### Geotechnical Instrumentation and Test Site Geology

Detailed geotechnical instrumentations were conducted at six sites over the past decade: 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 coreholes. 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.

### 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 gateroad 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. The FLAC3D finite difference program was selected since it has been calibrated and verified with field data from the Pittsburgh Seam.

## EFFECT OF OVERBURDEN DEPTH ON LONGWALL-INDUCED MAXIMUM LATERAL DEFORMATION AND VERTICAL ABUTMENT PRESSURE

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. However, large longwall-induced vertical pressure may induce unusually high casing stress, especially with a near-seam sharp soft-to-hark rock interface, leading to large casing deformation for a fully cemented production casing.

## 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. A 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 a thick limestone/sandstone layer, is expected to induce large post-mining subsurface and casing deformations.

## EFFECTS OF SURFACE TOPOGRAPHIC RELIEF

Figure 2 shows the surface layout and mine map overlay at a medium cover test site. Figure 2 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 this medium cover 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 medium cover 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 soft-to-hard 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.

## 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,

**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 (3810 psi) |
| 314 m (1,030 ft) | 13 mm (0.5 in) | 10.9 MPa (1580 psi) |
| 184 m (604 ft) | 108 mm (4.25 in) | 10.5 MPa (1523 psi) |
| 177 m (580 ft) | 38.1 mm (1.5 in) | 9.79 MPa (1420 psi) |
| 168 m (550 ft) | 43.2 mm (1.7 in) | 9.34 MPa (1355 psi) |
| 147 m (482 ft) | 168 mm (6.6 in) | 4.36 MPa (632 psi) |

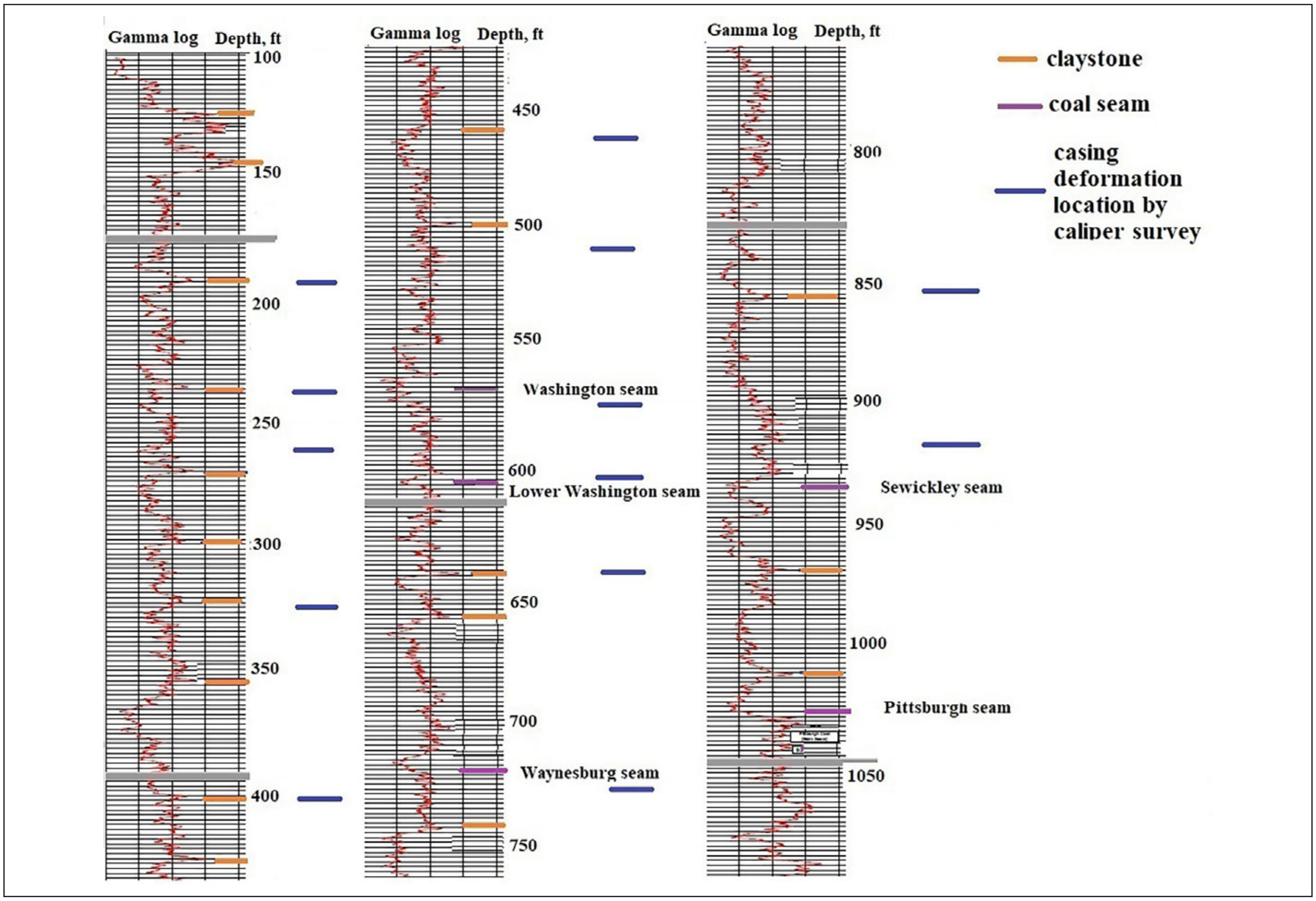


**Figure 1. Correlation between presence of soft-to-hard rock interfaces and measured post-mining casing deformation locations.**

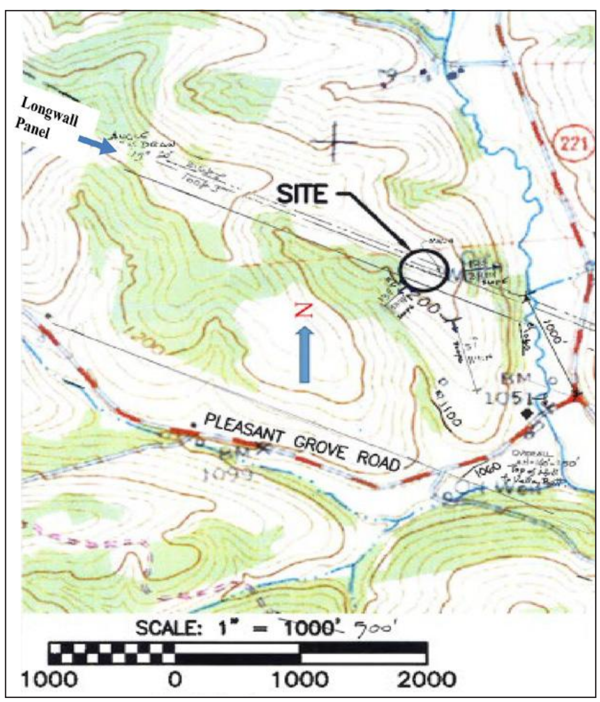


**Figure 2. Surface layout and mine map overlay at a medium cover test site**

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

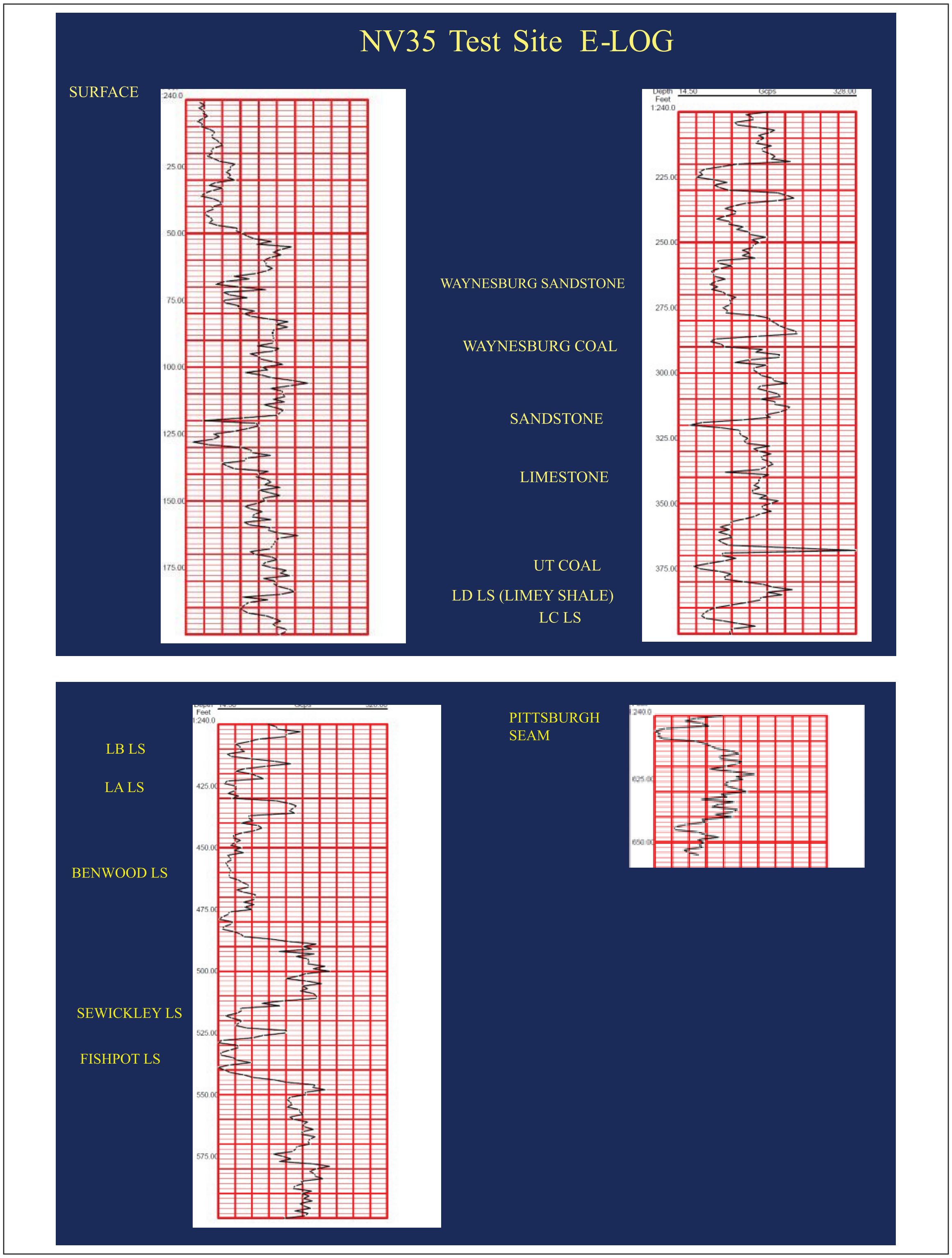


**Figure 3. Medium cover test site geology from an on-site E-log**

Figure 5. 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.

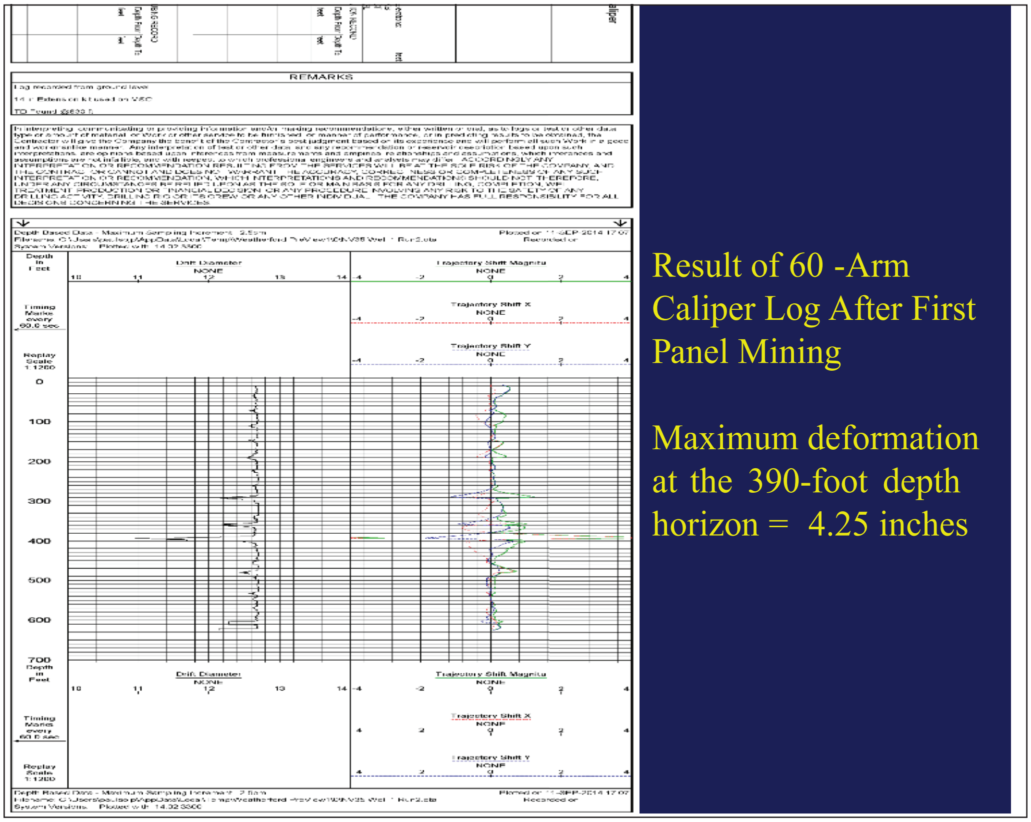


**Figure 4. Measured test well deformations from 60-arm Caliper survey at the medium cover (NV35) test site**

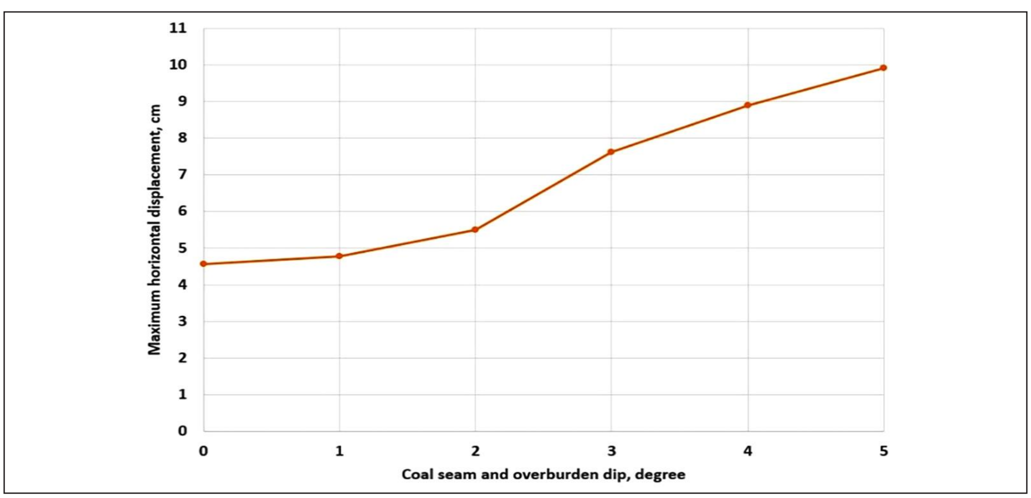


**Figure 5. Effect of strata dip on longwall-induced subsurface horizontal displacements at the medium cover (NV35) test site.**

## 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 6 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 7 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

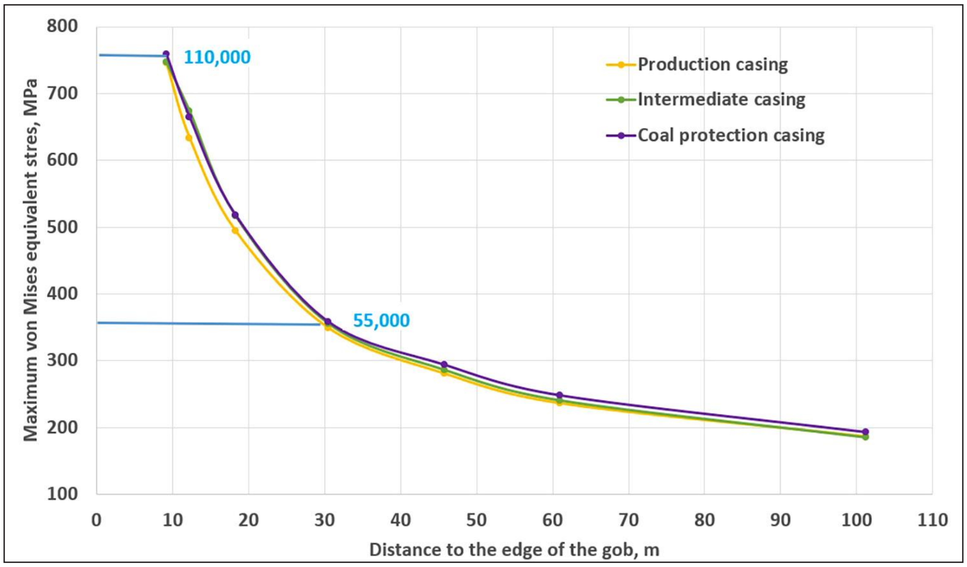


**Figure 6. Maximum von Mises stress in the coal protection, intermediate, and protection casings versus distance to the projected longwall recovery line (barrier pillar scenario)**

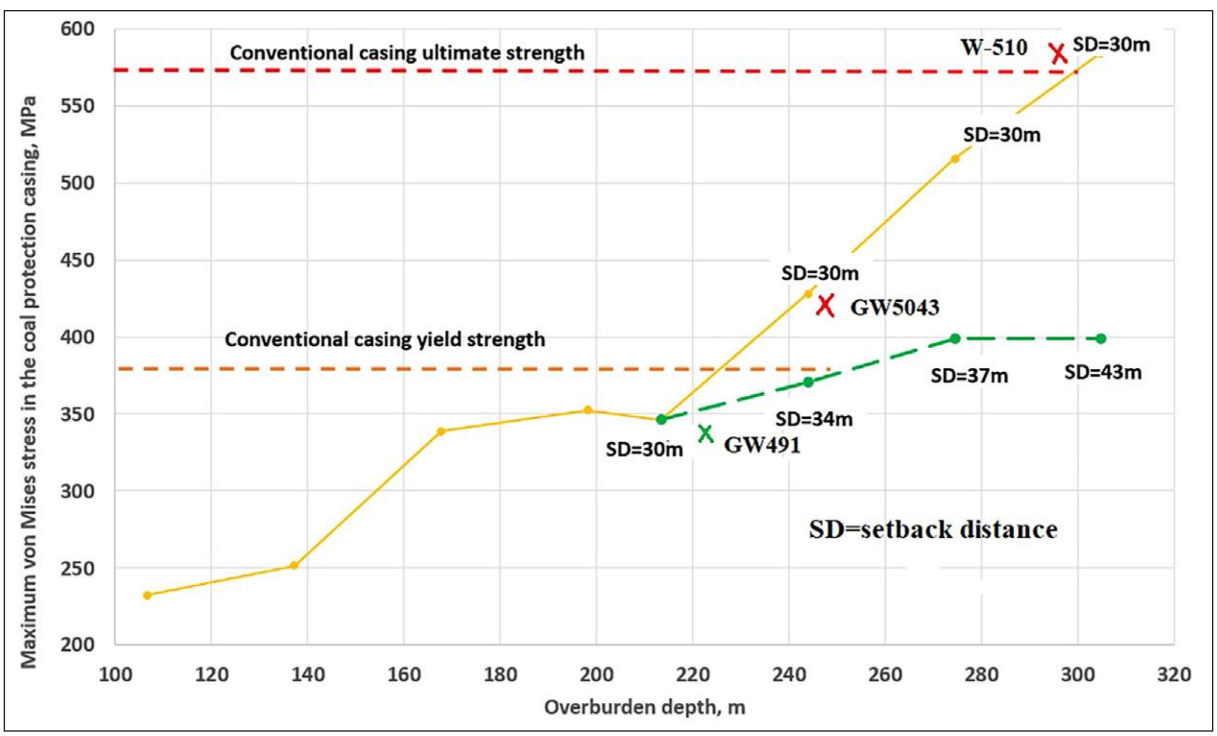


**Figure 7. Maximum von Mises stress in production casings versus the setback distance (chain pillar scenario)**

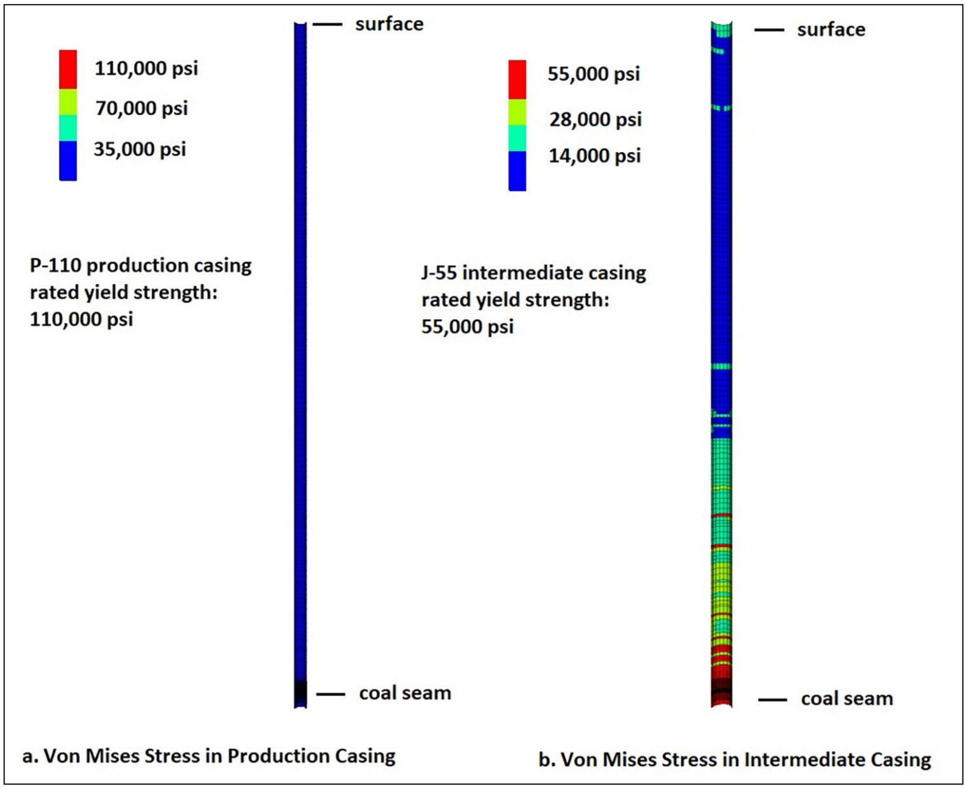


**Figure 8. Measured and computed subsurface deformations at the medium cover coal/gas industry test well site.**

stress in the production casing increases with overburden depth and decreases with increasing setback distance. Figure 7 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.

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

Figure 8 shows the effect of leaving the production casing uncemented. Since the annular space between the 9⅝" intermediate casing and the 5½" production casing is 3.365 inches, post-mining longwall-induced casing deformations smaller than 3.365 inches are not expected to cause any production casing deformation. In other words, leaving the production casing uncemented has a very high probability of uncoupling longwall-induced deformations from the production casing.

## 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.

## CONCLUSIONS

This paper presents recent 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, surface topography, strata dip, setback distance, and gas well construction. 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 traditional longwall subsidence studies, 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. 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 soft-to-hard rock interfaces are present near the bottom of stream valleys. 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.

## DISCLAIMER

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