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NIOSH Gas Well Stability Research: Investigation into the Causes of an Anomalous Shale Gas Well Casing Deformation at a Deep Longwall Mine

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ABSTRACT

Following the first longwall excavation at a deep-cover gas well site, the pre-mining modeling prediction of longwall-induced casing deformations in the fully cemented production casing were in excellent agreement with post-mining Caliper survey results. However, after second panel mining, the post-mining Caliper survey revealed a large plastic deformation near the top of the Pittsburgh Seam. The focus of this paper is to identify the possible cause of such an anomalous deformation. Very high longwall-induced casing stress near a thick claystone layer at 23 feet above the Pittsburgh seam horizon was identified as the primary cause. Leaving the production casing uncemented or using softer cementing material between intermediate and production casings is identified as the best practice.

INTRODUCTION

Since 2003, over 1,800 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 and Training (WVDOMS&T), 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), which indicate that longwall-induced horizontal displacements under shallow cover are one order of magnitude higher than those under deep cover; and longwall-induced vertical stresses under deep cover are one order of magnitude higher than those under shallow cover. Shale gas well casing and cementing alternatives were demonstrated to be one of the most important factors influencing longwall-induced deformations and stresses in the production casing (Su et al., 2023). This paper focuses on a recent case study that revealed an anomalous shale gas well casing deformation at a deep longwall mine.

CASE STUDY SITE AND STUDY SITE GEOLOGY

Case Study Site

This case study was a coordinated effort by the coal and gas industries, as well as by NIOSH and federal and state regulatory agencies, to evaluate the effect of deep cover on longwall-induced casing stresses and deformations. Figures 1 and 2 show 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. The longwall panel employed at this mine was 1,500-feet wide, and the average mining height was 7 feet. The abutment pillar below the gas well pad was 134 feet wide rib-to-rib. Five unconventional shale gas wells 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. Figure 4 shows the gas well casing construction and cementing details at the study site, which indicates that all casings are fully cemented.

FLAC3D MODELS AND STUDY SITE INSTRUMENTATION

FLAC3D Models

Prior to the collection of post-mining field measurements, a suite of FLAC3D finite difference simulations (Figure 5) 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 (>1,500 feet 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 1,500 feet away was the primary input to the model. Upon detection of the plastic casing deformation at the 1,284-foot horizon, an on-site gamma log was conducted, which revealed

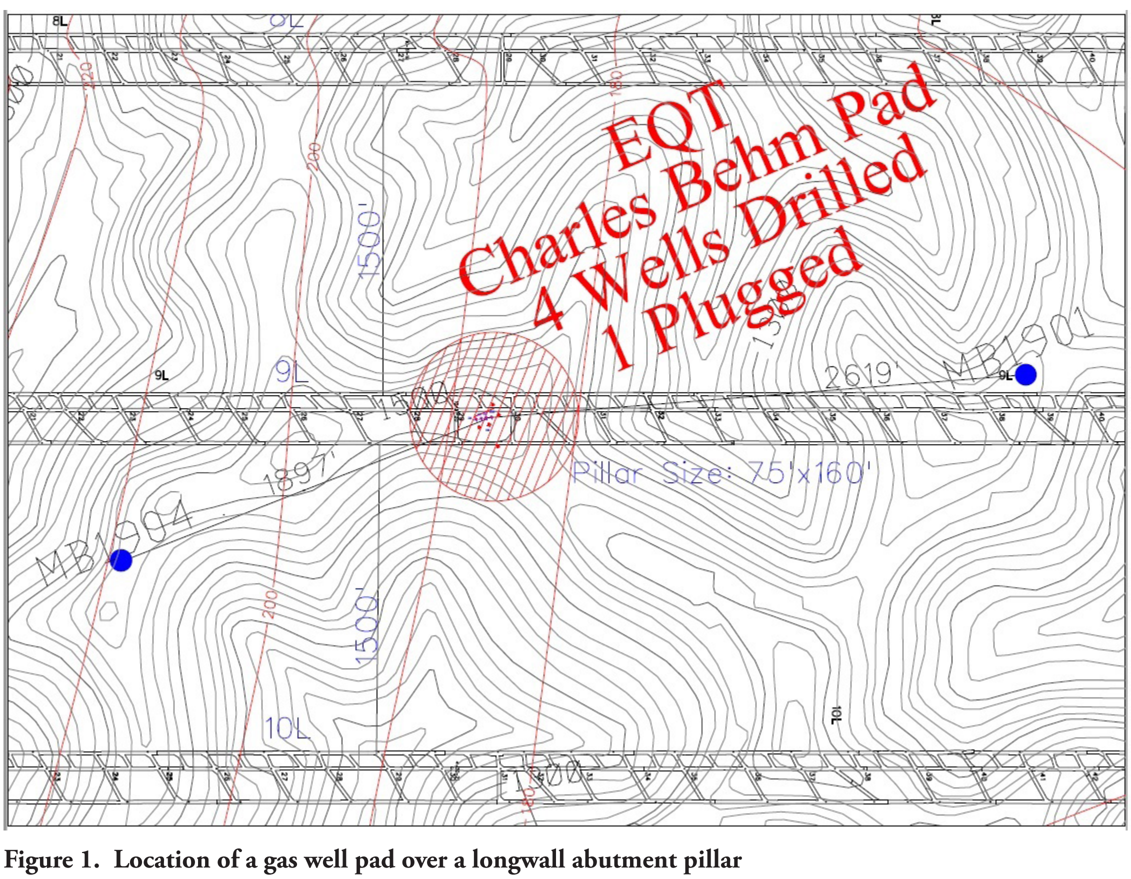


Figure 1. Location of a gas well pad over a longwall abutment pillar

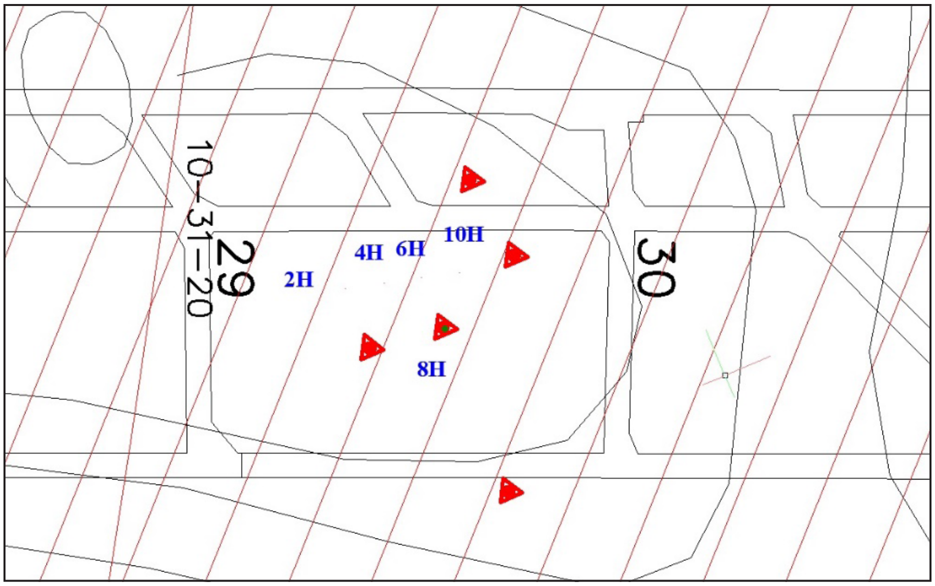


Figure 2. Detailed locations of the five gas wells over the longwall gate-road pillars

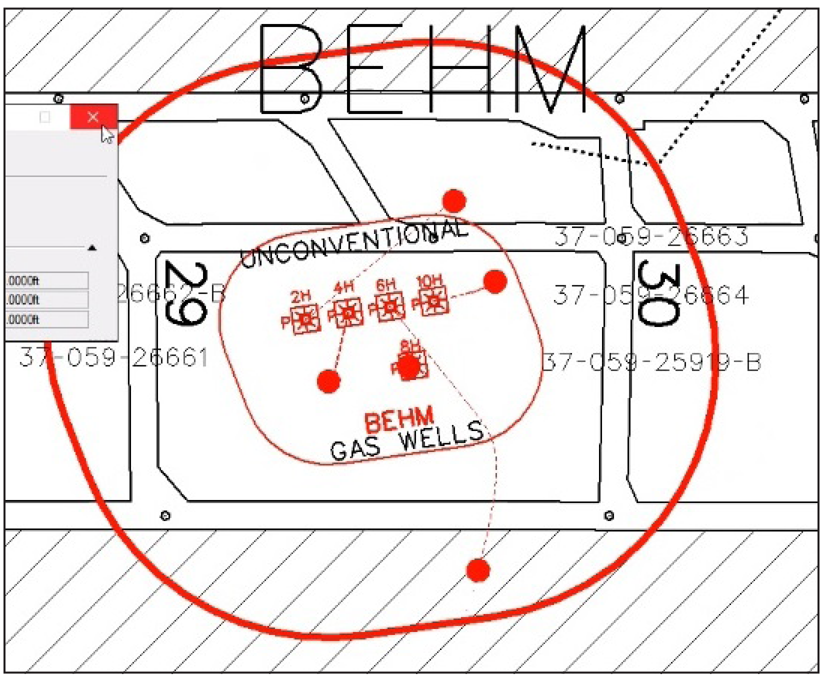


Figure 3. Actual gas well location at the Pittsburgh seam horizon versus the surface location due to well deviation

the presence of a thick claystone layer at 23 feet above the Pittsburgh seam. This thick claystone layer was not present in the core hole 1,500 feet 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. Specifically, many weak-to-strong rock interfaces were present and were simulated, 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 and measured casing diameter changes by the 40-arm Caliper surveys. The FLAC3D finite difference program was selected since it has been calibrated and verified with field data from the Pittsburgh seam. Figure 6 illustrates the longwall-induced pillar pressure at the deep-cover test site, which shows an

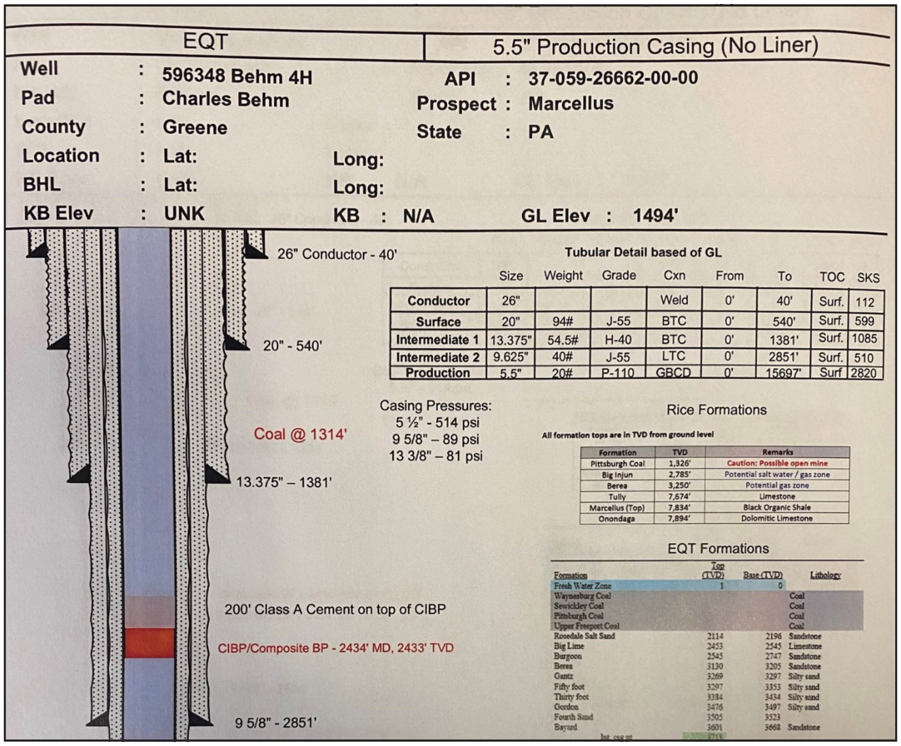


Figure 4. Gas well casing construction and cementing details at the study site

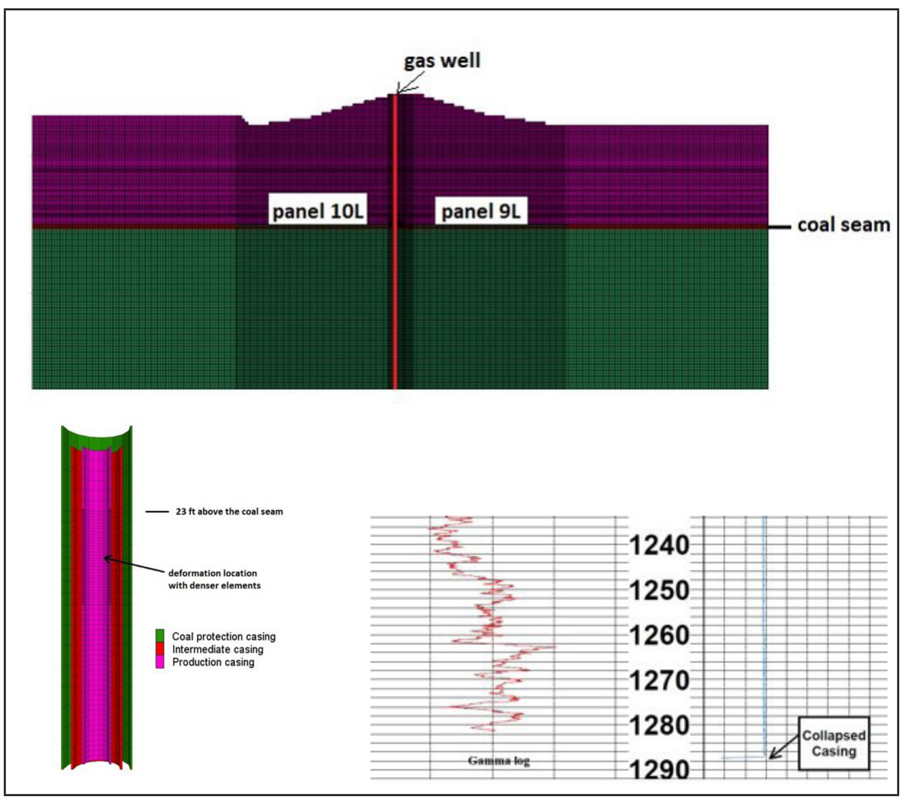


Figure 5. FLAC3D model of a gas well passing through the longwall abutment at the study site, along with a detailed on-site gamma log showing presence of a thick claystone layer at 23 feet above the Pittsburgh seam

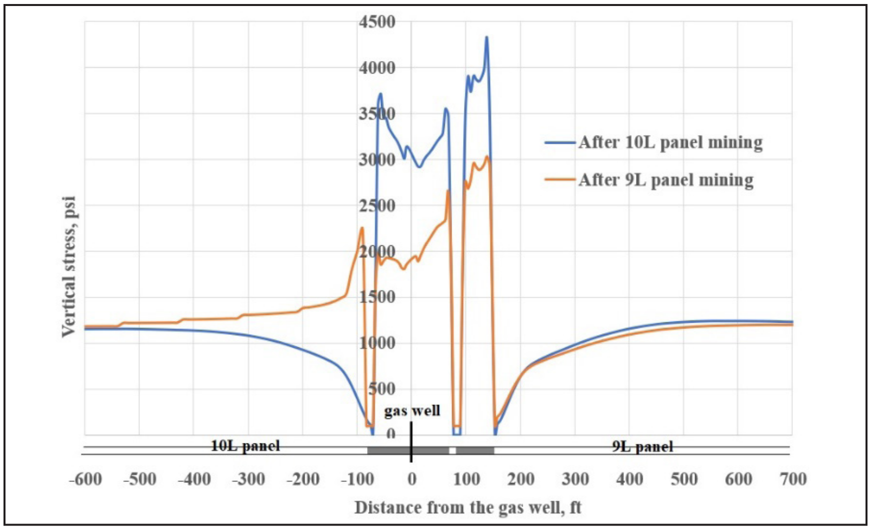


Figure 6. Longwall-induced vertical pillar pressure at the deep-cover test site

Horizontal Displacement and Production Casing Diameter Reduction

- Casing deformation at 642-ft depth after first and second panel mining
- Plastic casing deformation at 1284-ft depth after second panel mining

Predicted and Measured Production Casing Diameter Changes after First and Second Panel Mining

	First panel mining		Second panel mining		
Distance below the surface along the production casing, ft	Predicted casing diameter reduction, in	Measured casing diameter reduction, in	Predicted accumulated casing diameter reduction, in	Predicted total casing diameter reduction, in	Measured casing diameter reduction, in
475	0.2	0.06	0	0.2	0.2
642	**0.6**	**0.52**	**0.1**	**0.7**	**0.8**
675					0.2
750	0.2		0	0.2	0.1
800	0.05		0.05	0.1	0.1
890	0.05		0.05	0.1	0.1
975	0.02		0.03	0.05	0.2
1150	0.01		0	0.01	0.2
1284	0.02		0.02	0.04	**large deformation**
1310	0.28	0.21			

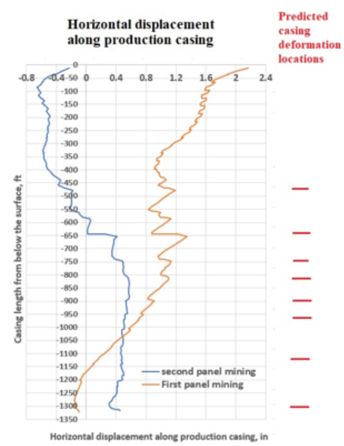


Figure 7. Predicted longwall-induced horizontal deformations and production casing diameter reduction

average pillar pressure of more than 3,000 psi at the gas well location and which is expected to impact the longwall-induced casing stresses. Figure 7 shows, prior to the availability of the on-site gamma log, the predicted longwall-induced horizontal displacement and casing deformations along the fully cemented 5-½" production casing by the FLAC3D model after first and second panel mining, which displays nine locations of very small casing deformation and one location of moderate casing deformation at 642 feet below the surface.

Comparison with Field Measurement

Post-first and post-second panel mining 40-arm Caliper surveys were conducted in the test well, 4H. Figure 8 shows the post-second panel mining 40-arm Caliper survey results in the fully cemented 4H production casing. Clearly, the predicted casing deformations shown in Figure 7 are in good agreement with the measured casing deformation shown in Figure 8, except the plastic deformation detected at the 1,284-foot horizon that prevented the 40-arm Caliper tool to pass through. Figure 8 also shows images of the moderate

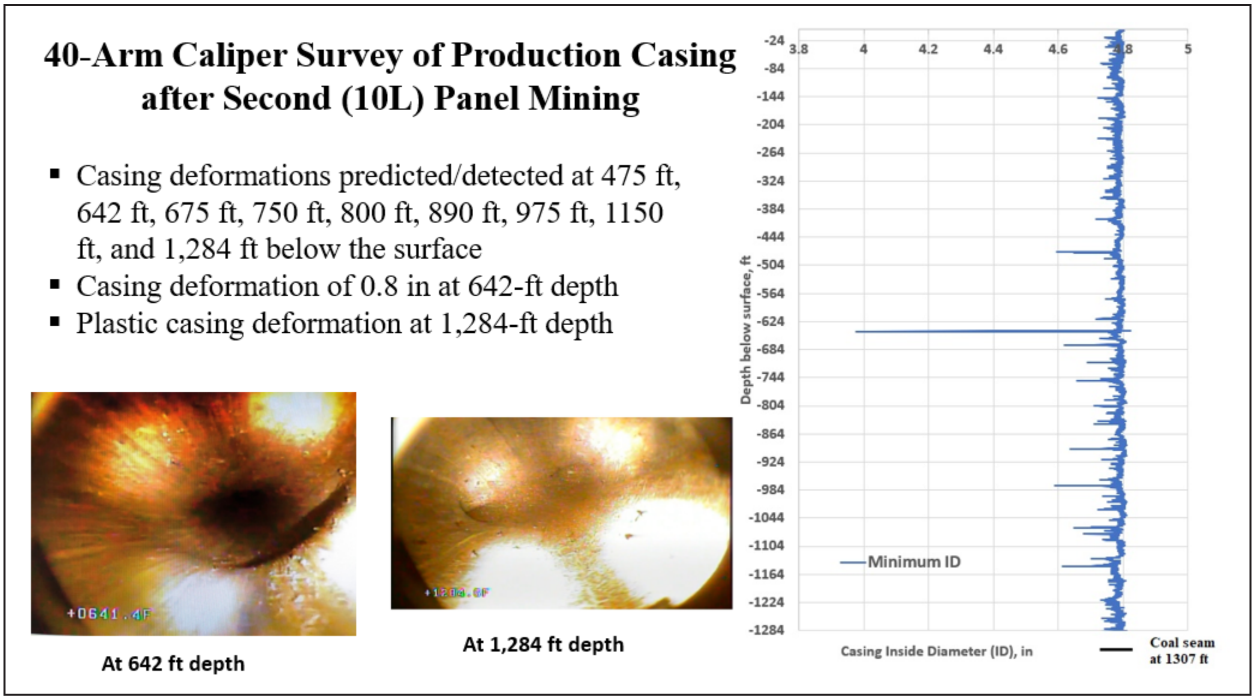


Figure 8. Measured production casing deformations (via 40-arm Caliper) after second panel mining and images of moderate and plastic casing deformations

casing deformation at the 642-foot horizon and the plastic casing deformation at the 1,284-foot horizon, as revealed by a downhole camera.

CAUSES OF PLASTIC CASING DEFORMATION AT THE 1,284-FOOT HORIZON

A few FLAC3D models were constructed to investigate the causes of plastic casing deformation at the 1,284-foot horizon. Figure 9 shows the longwall-induced casing stress at the deep-cover study site, where the depth to the Pittsburgh seam is 1,307 feet. Figure 9 only shows the high stress portion of the casing, which is located near the thick claystone horizon 23 feet 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 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 10 shows that, under a cover depth of 1,000 feet or less, longwall-induced deformations in fully cemented production casing are expected to stay in the elastic range. On the other hand, Figure 10 also indicates that strain hardening in fully cemented production casing is likely for cover depths up to 1,200 feet and plastic casing deformation is likely for cover depths greater than 1,200 feet.

EFFECT OF CASING CEMENTING ALTERNATIVES ON LONGWALL-INDUCED PLASTIC CASING DEFORMATION

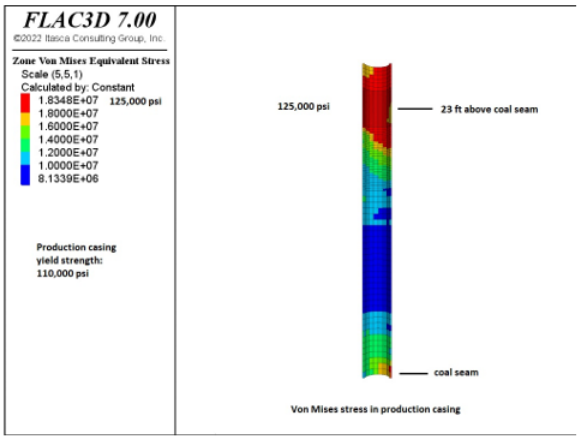
Since Figure 10 indicates that fully cemented production casing under more than 1,200 feet of cover could be subject to high longwall-induced stress and plastic casing deformation, it is then imperative to find engineering solutions to prevent such plastic casing deformation under deep cover. Figure 11 shows that, with uncemented production casing, longwall-induced casing stress is well below the rated yield strength of the P-110 casing under a cover depth of 1,307 feet. Similarly, with a gel-type softer cement between the intermediate and production casings, Figure 12 shows that longwall-induced casing stress is again well below the rated yield strength of the P-110 casing under 1,307 feet of cover.

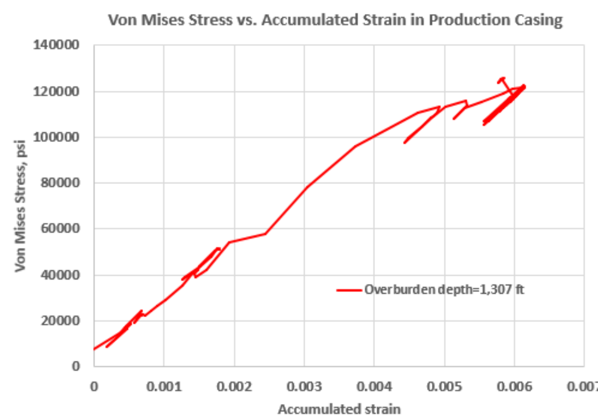
RESEARCH LIMITATION

Since this study represents the only gas well study site deeper than 1,200 feet, more data at similar deep-cover gas well sites are needed for definitive conclusions. FLAC3D simulations are purely modeling predictions, within the variance of the variables and parameters used, and need

Longwall-induced Von Mises Stress and Strain at the Deformation Location

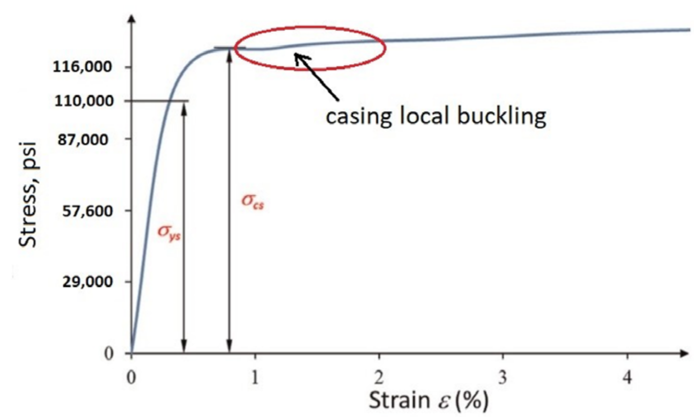
- Von Mises stress exceeds the P110 yield strength
- Von Mises stress reaches the P110 ultimate strength
- Plastic strain developed in the production casing





Possible Cause of Large Deformation above the Coal Seam Horizon

- Weak claystone layer induced high stress in the production casing
- Longwall-induced stress in production casing exceeds the yield strength of P-110 casing
- Large casing deformation occurred due to large plastic strain



Engineering stress–strain curve of P110 casing.

Figure 9. Longwall-induced production casing stress near the thick claystone horizon at the deep-cover study site (1,307 feet cover depth)

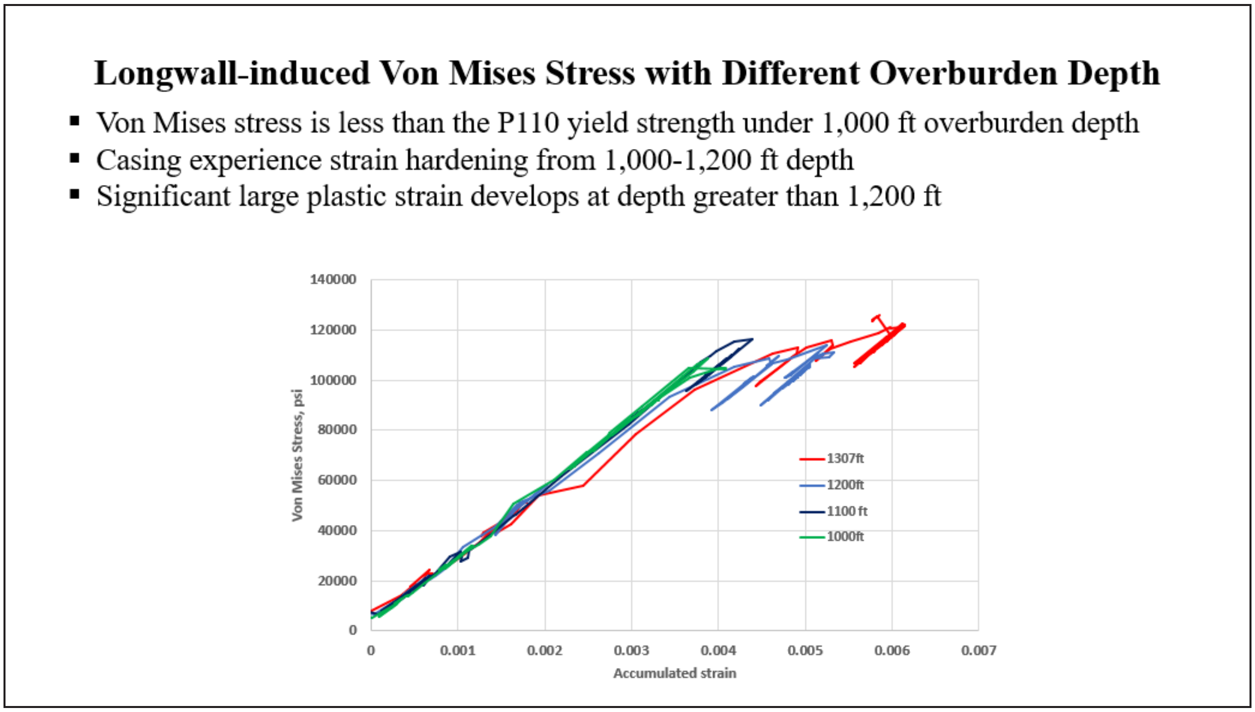


Figure 10. Effect of cover depth on longwall-induced casing stress and plastic casing deformation

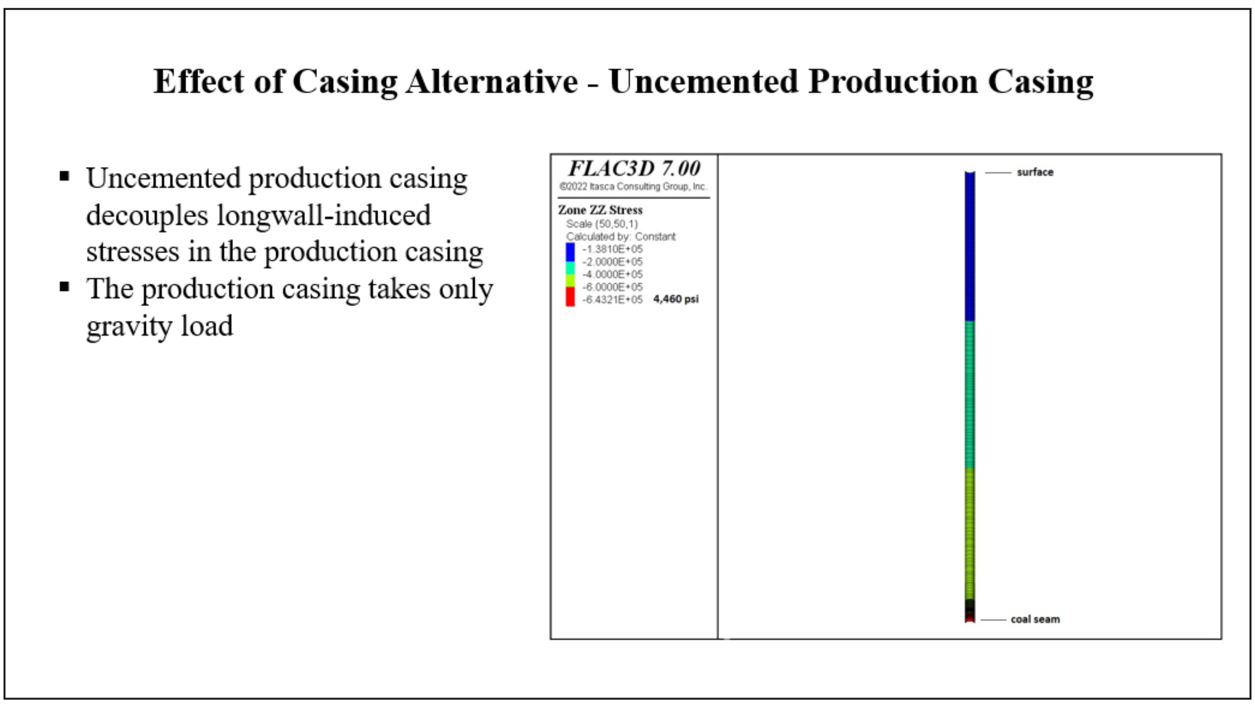


Figure 11. Effect of uncemented production casing on longwall-induced casing stress and plastic casing deformation at the deep-cover study site

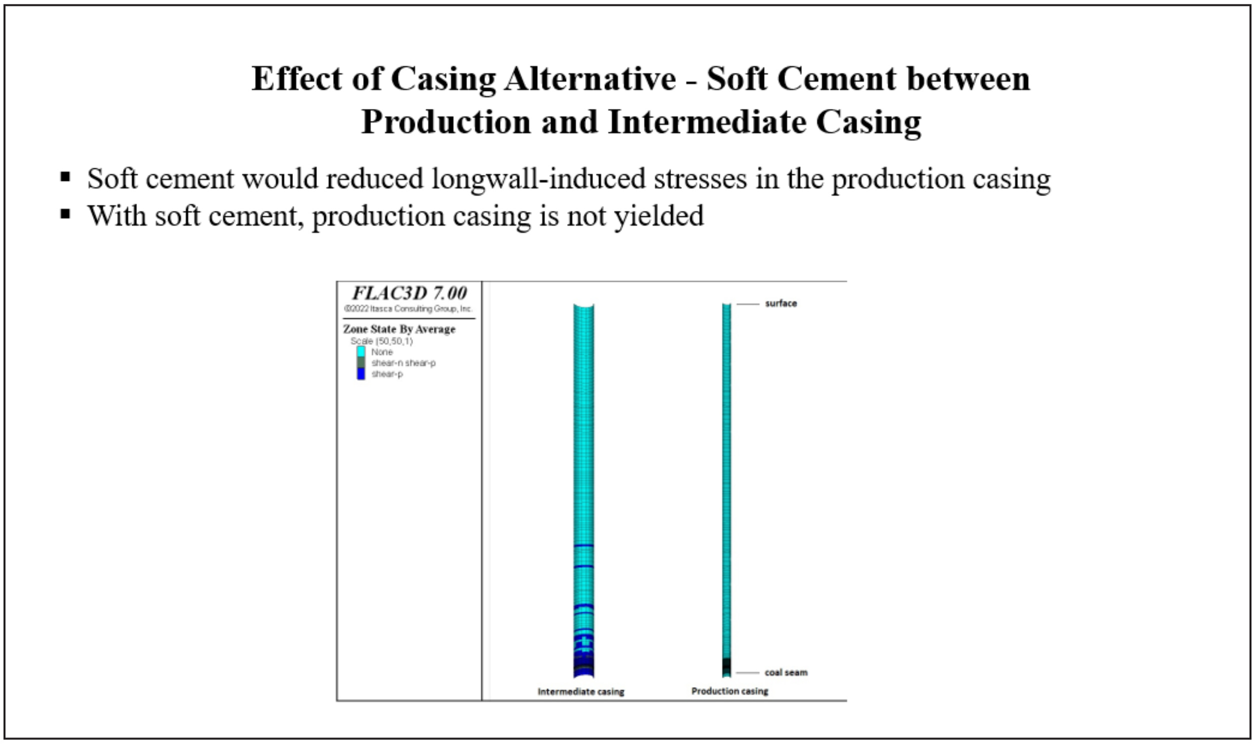


Figure 12. Effect of softer cement between intermediate and production casings on longwall-induced casing stress at the deep-cover study site

to be validated by actual field data. Similar deep-cover site data would need to be collected to enhance the data population to make the results statistically valid.

CONCLUSIONS

Following the first longwall excavation at a deep-cover gas well site, where the depth to the Pittsburgh seam is 1,307 feet, the pre-mining modeling prediction of longwall-induced casing deformations in the fully cemented production casing were in excellent agreement with post-mining Caliper survey results. After second panel mining, the post-mining Caliper survey revealed a large deformation near the top of the Pittsburgh seam, which prompted the acquisition of an on-site gamma log. This on-site gamma log revealed a thick claystone layer at 23 feet above the Pittsburgh seam horizon, which was not present in a core hole 1,500 feet from the study site. Revised FLAC3D models based on this new geologic detail reveal very high longwall-induced casing stress near a thick claystone layer at 23 feet above the Pittsburgh seam. Additional modeling results indicate that, under a cover depth of 1,000 feet or less, longwall-induced deformations in fully cemented production casing are expected to stay in the elastic range. On the other hand, strain hardening in fully cemented production casing is likely for cover depths up to 1,200 feet and plastic casing deformation is likely for cover depths greater than 1,200 feet. Leaving the production casing uncemented or using softer cementing material is identified as the best practice. This case study demonstrates that uncemented production casing or softer cementing material serves to uncouple longwall-induced deformations and stresses from the production casing. With proper gas well pillar sizing, leaving the production casing uncemented or using softer cementing material would allow for post-mining re-entry and resumption of gas production, which allows the coexistence of both coal and gas operations while safeguarding miner safety and health.

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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