

Lessons learned from Recent Longwall Mine-by Cases With Uncemented Casings



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ABSTRACT: Over 2,000 shale gas wells have been drilled in the longwall reserves of the Pittsburgh Coal Seam. When gas wells are in the vicinity of longwall mining, casing deformations are likely to occur due to longwall-induced subsurface movements and abutment stresses. One way to prevent casing deformation is to use a cementing alternative by leaving production casing uncemented. This paper presents three mine-by cases in which shale gas wells were in the chain pillars and the production casings were uncemented. These cases represent mine-by scenarios under shallow, medium, and deep cover. Casing deformations were measured with multi-finger caliper survey and predicted with numerical modeling. These mine-by case studies provide a general demonstration of how uncemented casing can uncouple production casing from longwall-induced stresses and deformations. Based on measurements of casing deformations and numerical modeling, the factors mentioned above are further analyzed to indicate in what conditions a cementing alternative may not eliminate production casing deformations. The knowledge gained from the mine-by case studies would help longwall operators and gas companies to optimize pillar design and casing design, thus minimizing the influence of longwall mining in the stability of shale gas wells in longwall pillars.

1. INTRODUCTION

With the shale gas boom, about 2,000 shale gas wells have been drilled through the current and future Pittsburgh coal reserves over the past 20 years. These shale gas wells, if located in longwall pillars, will be influenced by longwall mining. Longwall-induced subsurface ground movements would induce deformations in gas well casings. The concern is that if casing deformation is excessive, a casing breach could occur, and high-pressure shale gas could leak into the longwall mine with serious results. Because of the safety concern of gas wells in longwall pillars, the National Institute for Occupational Safety and Health (NIOSH) has been conducting research since 2016 to evaluate the effects of longwall mining on casing deformations under various mining depths and geological conditions.

NIOSH research has found that casing deformations are mainly caused by subsurface horizontal movements, especially under shallow and medium cover. NIOSH researchers have done several case studies with test wells in chain pillars under different overburden depths [Su (2016, 2017), Su et al. (2018, 2019), Zhang and Su (2021), and Zhang et al. (2022)]. These studies showed that longwall-induced relative horizontal displacements occur at weak-to-strong rock interfaces and are higher under shallow cover than under deep cover. The studies also showed that longwall-induced horizontal displacements are also affected by surface topography and strata dip.

Casing deformations are unavoidable if gas wells are situated in longwall chain pillars because gas wells must be subjected to longwall-induced horizontal displacements. One of the measures to minimize casing deformation is to use a cementing alternative, which is to leave the production casing uncemented from the surface to at least 30 m below the coal seam. Uncemented casing can generally uncouple longwall-induced deformations and stresses. NIOSH research has found that the level of longwall-induced horizontal displacements and casing deformations over chain pillars are generally less than the annulus between production and intermediate casing. If production casing is left uncemented, casing deformations can generally be eliminated.

This paper presents three mine-by case studies with gas wells in longwall chain pillars and the production casings uncemented. These mine-by cases represent longwall mining scenarios under shallow, medium, and deep cover. Casing deformations were measured with a multi-finger caliper survey and predicted with numerical modeling. Influential factors were further analyzed to show the conditions in which a cementing alternative may not be able to eliminate production casing deformations.

2. MINE-BY CASE #1 – GAS WELL AT A STREAM VALLEY UNDER SHALLOW COVER

This case consists of one gas well located in the chain pillars between two longwall panels in the Pittsburgh Coal Seam. Figure 1 shows the panel layout and gas well location. The longwall panels are 381-m wide, and the mining height is 2.3 m. The longwall panels are developed with a three-entry system with a total chain pillar width of 61 m center-to-center. The overburden depth at the gas well site is 168 m. With the first panel mining, the gas well setback distance is 16 m from the first panel gob. Figure 1 also shows the surface topography around the gas well. As the overburden depth contour lines show, the gas well is located at a stream valley with an elevation difference of 76 m between the valley bottom and the top of the hill.

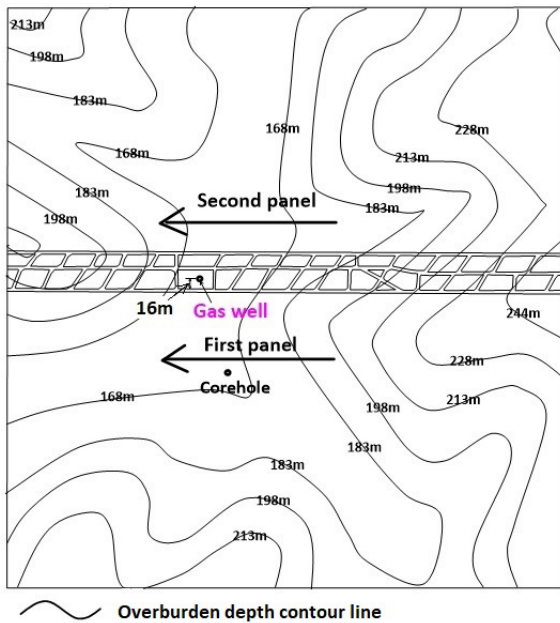


Fig. 1. Longwall panel layout and the location of the gas well in chain pillars.

Figure 2 shows the geologic column based on a corehole about 90 m away from the gas well. The column shows a typical Pittsburgh Seam overburden geology from the surface down to the coal seam. According to the corehole, the overburden consists of shale, clayshale, sandyshale, claystone, limestone, and sandstone. Many claystone layers and a few coal seams are present in the overburden and are identified as weak interfaces. Massive sandstone layers are present below 30-m depth, and massive limestone layers are present below 100-m depth.

The gas well was constructed with two casings. One 24.4-cm J55 intermediate casing was fully cemented in a 31.1-cm hole from the surface to a 148-m depth. The thickness of the intermediate casing was 0.635 cm. The M-50 production casing was 17.78 cm in diameter and was uncemented to a 194-m depth. The thickness of the production casing was 0.69 cm. The uncemented production casing gave a 5.4-cm open annulus between the intermediate and production casings.

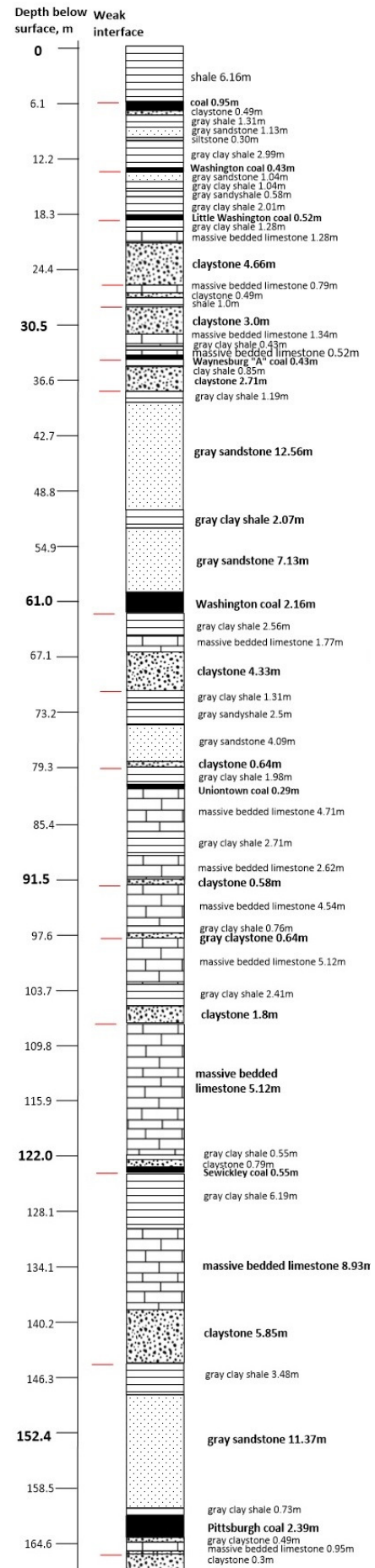


Fig. 2. The Overburden geology and interface locations.

Production casing was surveyed by a 60-arm caliper as each panel was mined. Figure 3 shows measured minimum inside diameters along the production casing after first panel mining. Casing deformations occurred at the locations with casing inside-diameter changes. A casing deformation of 0.25 cm was detected at a 97.6-m depth. After second panel mining, the production casing was surveyed again by a 60-arm caliper and the results are shown in Figure 4. A casing deformation of 1 cm was detected at a new location at 29-m depth. The deformation induced by first panel mining at 97.6-m depth increased slightly to 0.5 cm. These casing deformations occurred when the production casing was uncemented. It can be inferred that the deformations in the intermediate casing must have exceeded the open annulus of 5.4 cm between the intermediate and production casings.

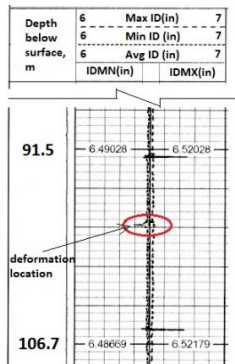


Fig. 3. Measured minimum inside diameters along the production casing after first panel mining. Casing deformation was detected at 97.6-m depth.

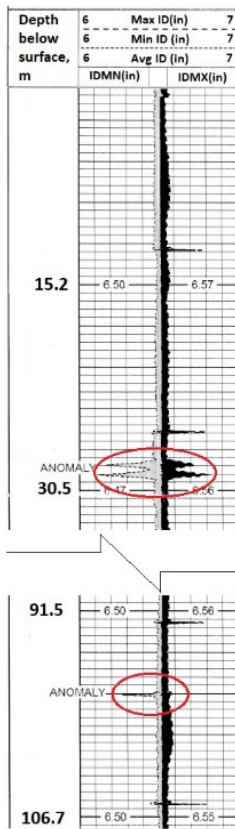


Fig. 4. Measured minimum inside diameters along the production casing after second panel mining.

FLAC3D modeling was used to predict casing deformations as each longwall panel was mined (ITASCA, 2017 and Zhang et al. (2023a)). Figure 5 shows a cross-sectional view of the FLAC3D model. The model was set up based on site-specific overburden geology. The rock layers and weak interfaces were modeled according to the closest corehole as shown by the geologic column in Figure 2. An interface friction angle of 11.3 degrees was assigned to all the interfaces in the model. Gas well casings were modeled according to their specifications. Surface topography was considered in the model. Longwall mining was modeled to induce surface and subsurface movements in the model as each panel was mined.

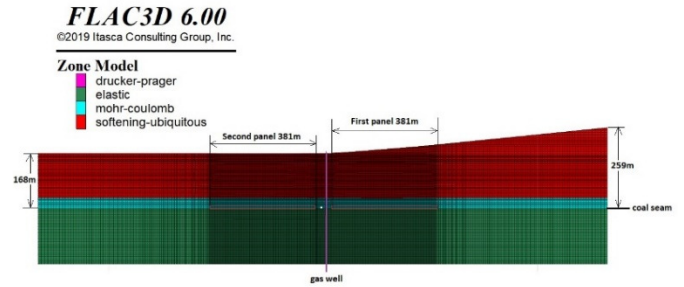


Fig. 5. Cross-sectional view of the FLAC3D model.

The model predicted horizontal displacement along the intermediate casing after first and second panel mining as shown in Figure 6. With first panel mining, the casing moves towards the first panel gob. At the surface, the casing moves about 2 cm towards the first gob. In the subsurface, the casing is subjected to relative horizontal displacements or shear displacements at interface locations. Casing deformations are caused by relative horizontal displacements along strong/weak rock interfaces. Based on the horizontal displacement curve, the casing deformations are predicted at 4 locations. Table 1 shows a comparison between predicted and measured casing deformations after first and second panel mining. Two relatively large intermediate casing deformations are predicted at 29 m and 98 m below the surface. Considering that casing deforms on two opposite sides, casing deformation is estimated by 1.4 times the relative horizontal displacement (Zhang et al. 2022). If the intermediate casing deformation exceeds the open annular space of 5.4 cm, the intermediate casing would be in touch with the production casing and cause it to deform. The estimated production casing deformation is 0.66 cm at 29-m depth and 0 at 98-m depth, and the actual casing deformation is 0 and 0.25 cm after first panel mining. After second panel mining, the estimated production casing deformation is 1.19 cm at 29 m depth and 0.30 cm at 98-m depth, and the actual casing deformation is 1.02 cm at 29-m depth and 0.51 cm at 98-m depth.

Table 1. Comparison between predicted and measured casing deformations after first and second panel mining.

Depth below surface, m	Predicted relative displacement along intermediate casing after first panel mining, cm	Predicted accumulated relative displacement along intermediate casing after second panel mining, cm	Estimated production casing deformation after first panel mining, cm	Actual production casing deformation after first panel mining, cm	Estimated production casing deformation after second panel mining, cm	Actual production casing deformation after second panel mining, cm
29	4.32	4.70	0.66	0.00	1.19	1.02
63	0.51	0.76	0.00	0.00	0.00	0.00
79	0.38	0.51	0.00	0.00	0.00	0.00
98	3.30	4.06	0.00	0.25	0.30	0.51

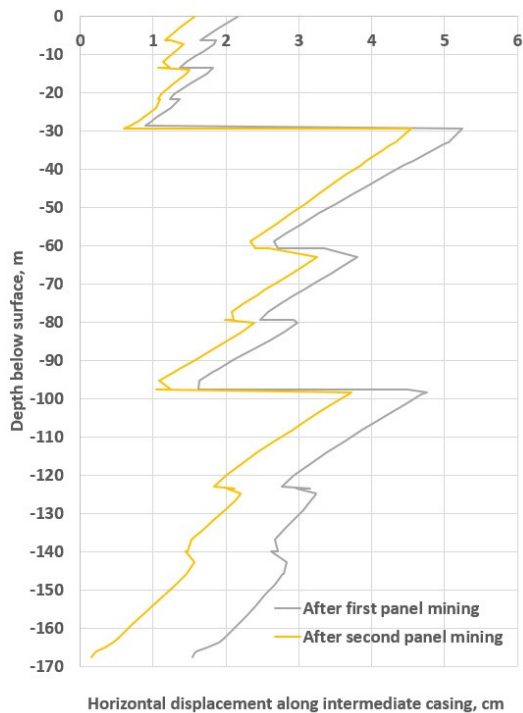


Fig. 6. Predicted horizontal displacements along the intermediate casing after first and second panel mining.

In this case, casing deformations occurred in the uncemented production casing as the longwall-induced deformations in the intermediate casing exceeded the open annulus between the two casings. The occurrence of casing deformations is associated with the presence of massive sandstone and limestone in the overburden. The relatively large deformation at the shallow depth of 29 m is also associated with the stream valley where claystone layers could be saturated. This case suggests that casing deformations could occur in uncemented production casing if the gas well is in chain pillars under shallow cover and at a stream valley.

3. MINE-BY CASE #2 – GAS WELLS IN CHAIN PILLARS UNDER MEDIUM COVER

In this case, five shale gas wells are located in the chain pillars between two adjacent longwall panels in the Pittsburgh Seam. Figure 7 shows the chain pillar dimensions and gas well locations. The five shale gas wells are located at the center of the large, abutment pillar. These gas wells are 30.5 m away from the first longwall gob, and 16.5 m from the second longwall gob. The longwall panels are 367-m wide with a mining height of 2.1 m. The overburden depth at the well pad is 204 m. The wells are named 1H, 2H, 3H, 6H, and 7H. The first panel mined-by the gas wells in March 2022, and the second panel mined-by was in October 2022.

Figure 8 shows the overburden geology with gamma and density logs from the closest corehole to the well pad. The overburden at the gas well site consists mainly of shale, sandshale, claystone, sandstone, and limestone. Weak claystone and coal interfaces are identified by correlating the core, gamma, and density logs as shown in Figure 8. These

interfaces represent weak beddings where casing deformations could occur.

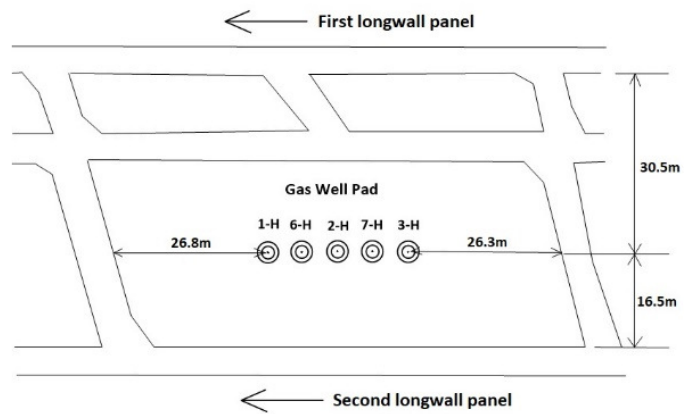


Fig. 7. Gas well pillar layout.

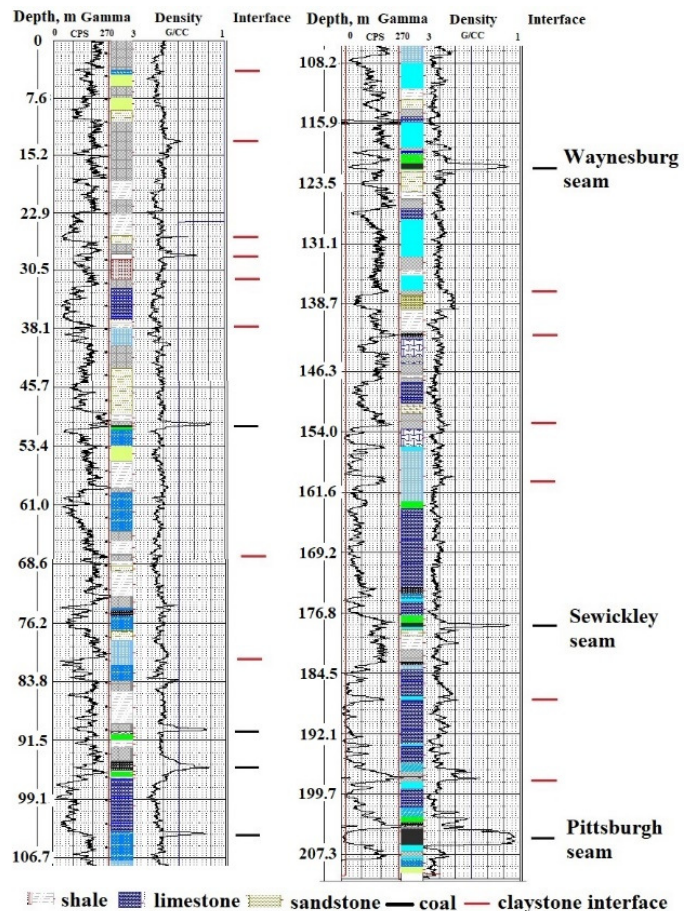


Fig. 8. Overburden geology with Gamma and density logs (Zhang et al. 2023a).

Each shale gas well was constructed with four casings: water protection casing, intermediate casing, production casing, and additional casing. The production casing and intermediate casing ran past the Pittsburgh Coal Seam. The depth of the intermediate casings ranged from 553 m to 642 m, all cemented to the surface. The production casings of wells 2H, 3H, 6H, and 7H were uncemented from the surface to a 1,247-m depth leaving an open annulus of 8.47 cm between production casing and intermediate casing. The cement top of the 1H production casing was detected below the surface based on the Cement Bond Log (CBL). The top of good cement was detected at 163

m below the surface, and the top of highest lower-quality cement stringers was detected at 137 m below the surface. The production casing in 1H well above a 137-m depth was uncemented. Water protection casings in all wells were set at depths ranging from 114 m to 115 m, all cemented to the surface. Wells 1H, 2H, and 6H each had an additional casing string set at depths ranging from 172 m to 173 m, all cemented to the surface.

Longwall-induced casing deformations were surveyed through the production casing with a 40-arm caliper in each of the five wells after each panel was mined. No casing deformations were detected in the uncemented production casing in the 2H, 3H, 6H, and 7H wells. Figure 9 shows the 40-arm caliper survey results for well 7H. The measurement shows that the casing inside diameter along the production casing has no changes from the surface down to the coal seam.

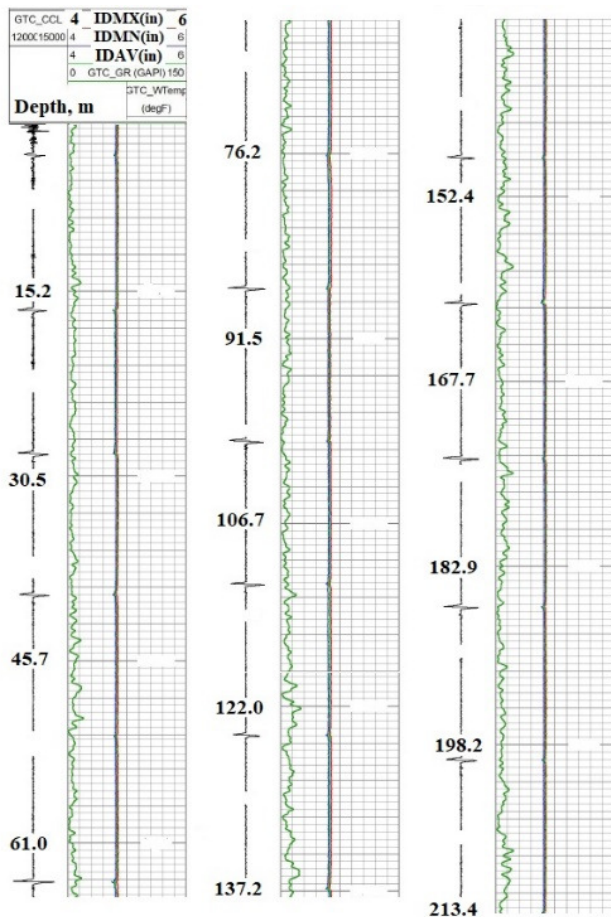


Fig. 9. Forty-arm caliper survey of the inside diameters showed no deformations along the production casing in well 7H after second panel mining (IDMN is the minimum inside diameter; IDMX is the maximum inside diameter; and IDAV is the average inside diameter).

For the well 1H with partially uncemented casing, a 40-arm caliper survey was also conducted after first and second panel mining. Figure 10 shows 40-arm caliper survey results along the production casing in well 1H after first panel mining. The nominal casing inside diameter for the 14-cm production casing is 12.2 cm. The figure shows that the casing diameter is slightly reduced by about 0.05 cm at 137-m depth. Figure 11 shows 40-arm caliper survey results for the same well after second panel

mining. The survey results show that the casing inside diameter is reduced by about 0.15 cm at 137 m depth. Slight deformations also occurred at three other locations below the 137-m depth where the casing was cemented with lower quality cement.

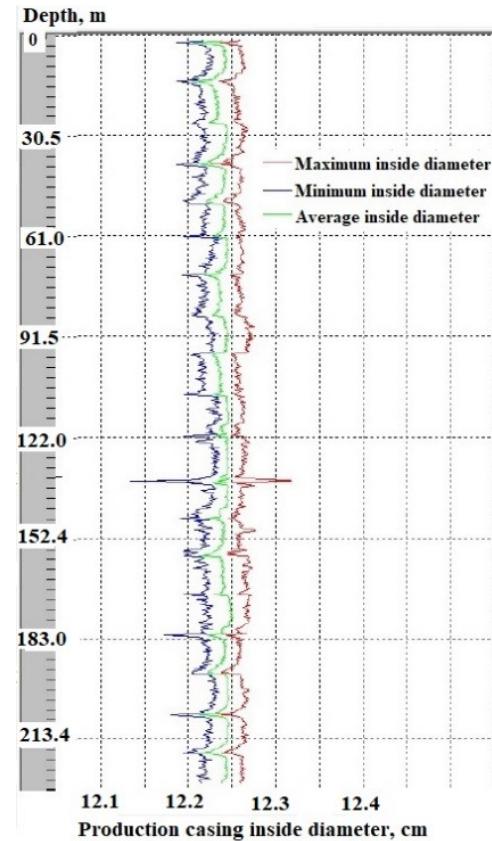


Fig. 10. Forty-arm caliper measured inside diameters along the production casing in well 1H after first panel mining (Zhang et al. 2023a).

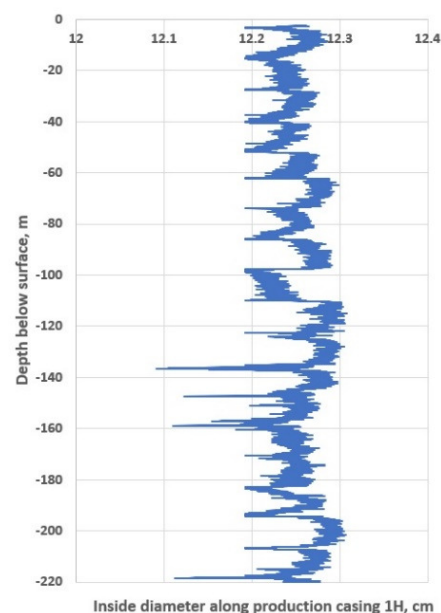


Fig. 11. Forty-arm caliper measured inside diameters along the production casing in well 1H after second panel mining (Zhang et al. 2023a).

Casing deformations are also predicted by the numerical model established with site-specific conditions. To predict production casing deformations, potential deformations in the intermediate casing were predicted first. If the intermediate casing deformation is less than the open annulus between the intermediate and production casing, no deformation would be induced in the production casing. Figure 12 shows the predicted horizontal displacement along the intermediate casing after first and second panel mining. Predicted casing deformation locations are shown at the interfaces with relative horizontal displacement. The model predicted casing deformations at 8 locations below the surface. Table 2 shows a summary of the predicted deformations in the intermediate casing. Casing deformations are predicted at the same location after first and second panel mining. Generally, casing deformations are small, but two relatively large deformations are predicted at 79 m and 137 m below the surface. As these deformations are less than the open annular space between production and intermediate casing, no deformation is predicted in the uncemented production casing.

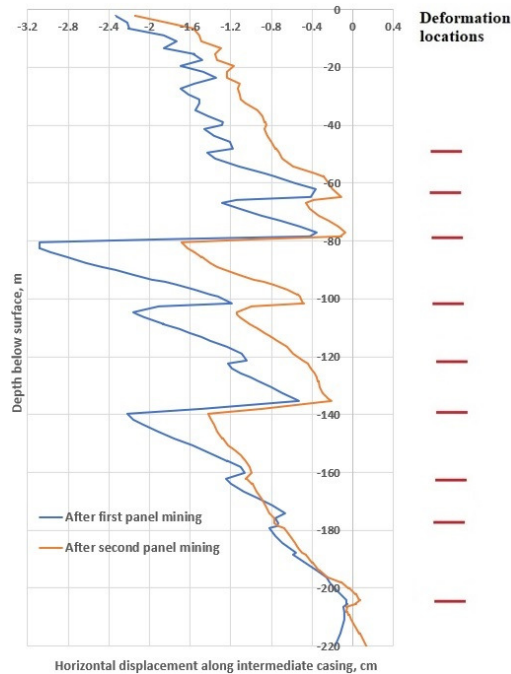


Fig. 12. Predicted horizontal displacement along intermediate casing after first and second panel mining.

Table 2. Predicted deformations in the intermediate casing after first and second panel mining.

Depth below surface, m	Predicted relative horizontal displacement after first panel mining, cm	Predicted relative horizontal displacement after second panel mining, cm	Predicted casing diameter change after first panel mining, cm	Predicted casing diameter change after second panel mining, cm
48	0.25	0.00	0.36	0.71
64	1.02	0.46	1.42	2.06
79	2.67	1.27	3.73	5.59
105	1.02	0.25	1.42	1.78
122	0.20	0.23	0.28	0.61
137	1.78	0.51	2.49	3.20
162	0.15	0.13	0.21	0.38
174	0.13	0.13	0.18	0.36
204	0.00	0.13	0.00	0.18

Both measurement and model prediction in this case showed that no casing deformation occurred in the uncemented production casing. This suggests that with normal overburden

geology under medium cover, longwall-induced casing deformations in the intermediate casing is less than the open annular space of 8.47 cm. This mine-by case also shows that if casings are fully cemented, casing deformations would occur in the production casing. But small casing deformations may not affect casing integrity. In this case, all the five shale gas wells passed the pressure test after second panel mining and returned to normal production after being interrupted for a few months during the period of the mine-by.

4. MINE-BY CASE #3 – GAS WELLS IN CHAIN PILLARS UNDER DEEP COVER

Three shale gas wells are located in the chain pillars between two adjacent longwall panels in the Pittsburgh Coal Seam. The overburden depth at the well pad is 311 m. Figure 13 shows the chain pillar dimensions and gas well locations. One gas well was surveyed by a 40-arm caliper after first and second panel mining. The setback distance of this gas well is 20.7 m to the first panel.

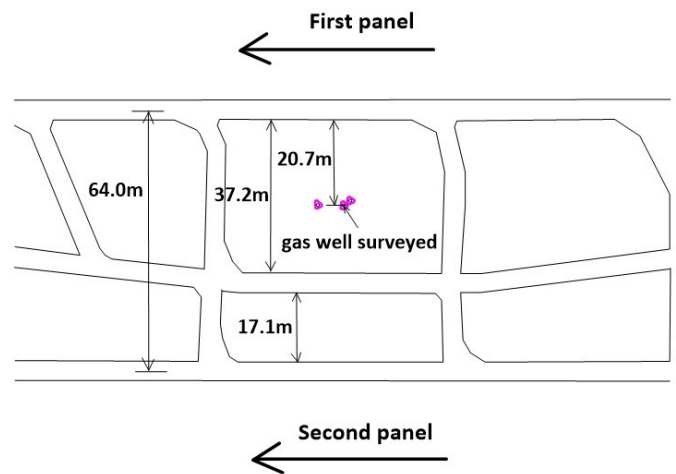


Fig. 13. Gas well pillar layout.

Gas wells are constructed with four casings: conductor casing, coal protection casing, intermediate casing, and production casing. Three casings pass through the Pittsburgh Coal Seam. The coal protection casing and intermediate casing are fully cemented, but the production casing is uncemented from the surface to a 1,365-m depth, which leaves an open annular space of 8.47 cm between the production and intermediate casing.

Figure 14 shows the overburden geology from the closest corehole to the well pad. The overburden at the gas well site consists mainly of shale, sandshale, claystone, sandstone, limestone, and shaley limestone. No thick massive beds are present in the overburden. Weak interfaces are identified at claystone layers, coal seams, and bedding planes between weak and strong massive layers.

A 40-arm caliper survey was conducted through the production casing after first panel mining. Figure 15 shows the survey results of the inside diameter along the production casing after first panel mining. As the casing inside diameters had no change, no deformation was detected in the production casing after first panel mining. After second panel mining, the

production casing was surveyed by a 40-arm caliper again, and no deformation was detected in the production casing.

Casing deformations were modeled with FLAC3D software using site-specific overburden geology. Figure 16 shows the predicted horizontal displacement along the intermediate casing. Table 3 summarizes the predicted casing deformations. Casing deformations were predicted at 11 locations below the surface. The predicted maximum casing deformation was 2.4 cm at a 191 m depth after first panel mining and 3.8 cm at the same depth after second panel mining. Since the maximum casing deformation in the intermediate casing is smaller than the open annular space of 8.47 cm between production and intermediate casing, no deformations are predicted in the production casing after both first and second panel mining.

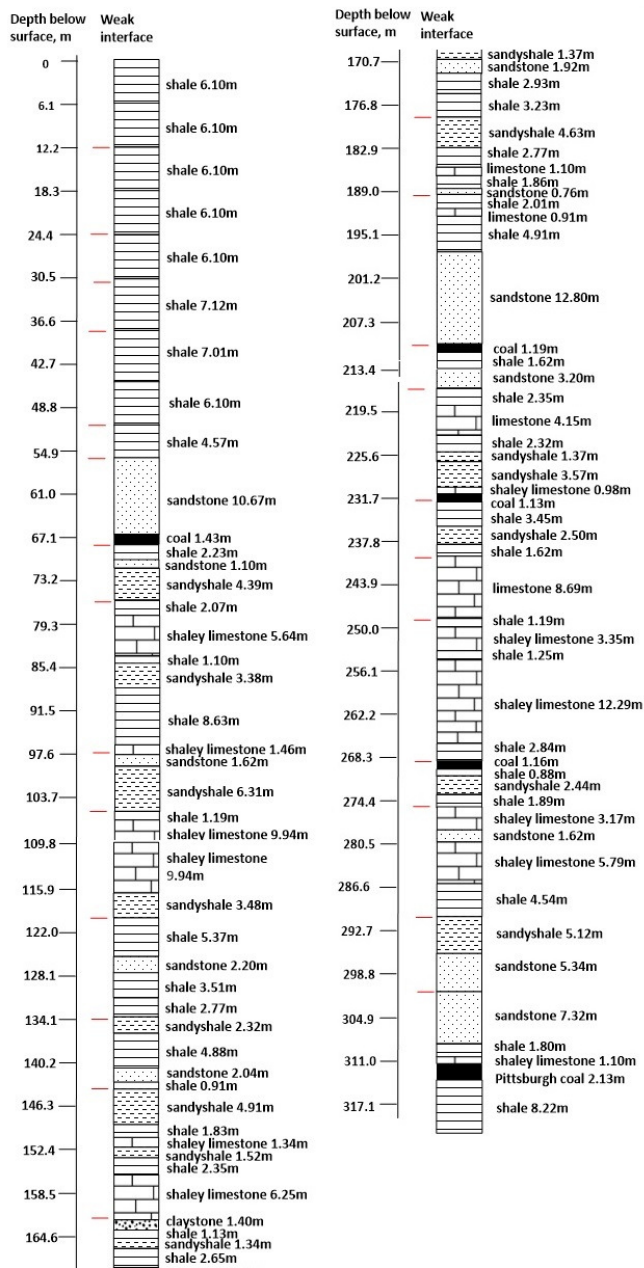


Fig. 14. Overburden geology and interface locations.

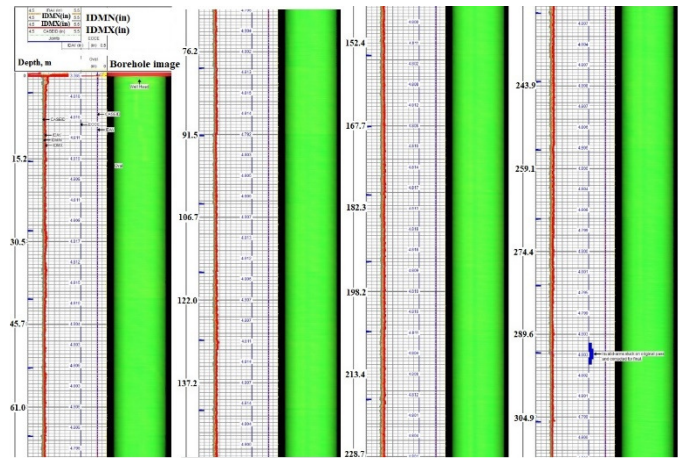


Fig. 15. Forty-arm caliper survey of the inside diameter showed no deformations along the production casing after first panel mining (IDMN is the minimum inside diameter; IDMX is the maximum inside diameter).

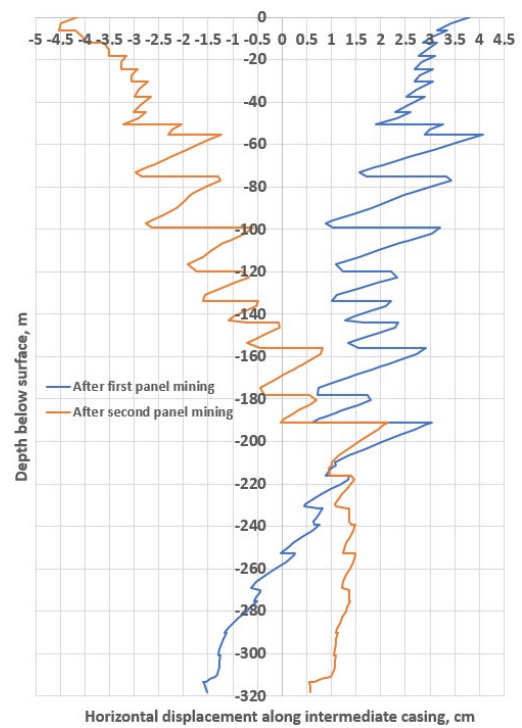


Fig. 16. Predicted horizontal displacements along the intermediate casing after first and second panel mining.

Table 3. Predicted deformations in the intermediate and production casings after first and second panel mining.

Depth below surface, m	After first panel mining	After second panel mining		
	Predicted relative horizontal displacement along intermediate casing, cm	Predicted accumulated relative horizontal displacement along intermediate casing, cm	Predicted intermediate casing deformations, cm	Predicted production casing deformations, cm
49	1.2	0.3	1.8	0.0
55	1.1	0.5	2.0	0.0
76	1.7	0.1	2.3	0.0
98	2.1	0.6	3.4	0.0
122	1.0	0.1	1.4	0.0
143	1.0	0.5	2.0	0.0
159	1.3	0.3	2.1	0.0
177	1.0	0.2	1.6	0.0
191	2.4	0.5	3.8	0.0
216	0.5	0.1	0.7	0.0
232	0.3	0.1	0.4	0.0

This mine-by case suggests that under deep cover up to 311 m, deformations in intermediate casing above the coal seam horizon are so small that an open annulus of 8.47 cm between production and intermediate casing is sufficient to uncouple the production casing from longwall-induced stresses and deformations. The small longwall-induced casing deformations under deep cover is due to high abutment pressure and high frictional resistance along weak interfaces over the chain pillars.

5. EFFECTIVENESS OF UNCEMENTED CASING IN ELIMINATING PRODUCTION CASING DEFORMATIONS

Casing deformations are affected by many factors such as overburden depth, surface topography, interface friction, setback distance, and the open annulus between production and intermediate casing. These factors will largely determine whether the deformations in the production casing can be eliminated if it is left uncemented.

Along with the instrumentation study, Su (2017) investigated the effect of overburden depth and casing cementing alternatives on the longwall-induced stresses and deformations in gas well casings. Su (2017) found that, under deep cover, smaller lateral strata deformation was present in the overburden above the mining horizon, but higher pressure and deformation were present at and below the coal seam. Su (2017) also illustrated that leaving the intermediate and production casings uncemented from 15 m below the seam to the surface can effectively uncouple the ground and the casings, making the two inside casings free from the influence of longwall-induced deformations.

Casing deformations above the mining horizon are mainly caused by longwall-induced horizontal ground movements. For Pittsburgh Seam overburden geology, the relative horizontal displacements along weak interfaces are usually small. As the three mine-by cases in this study show, the maximum longwall-induced deformation in the intermediate casing is less than the typical annulus of 8.47 cm between production and intermediate casing. With normal overburden geology, an uncemented production casing can generally eliminate deformations in production casing above the mining horizon. The cementing alternative is more effective under medium and moderate deep cover because longwall-induced horizontal displacements tend to be smaller under deeper cover.

Under deep cover, casing deformation could occur at the coal seam horizon with weak claystone layers even if the production casing is uncemented. High abutment pressure under deep cover could induce high stress and cause local buckling failure in the intermediate casing. Collapse of the intermediate casing could induce deformations in the production casing. In a case study of a conventional gas well in chain pillars under a deep cover of 293 m, Zhang et al. (2019) reported an occurrence of large casing deformation at a claystone layer 4.6 m below the coal seam in the uncemented production casing.

Under shallow cover, casing deformations are affected by surface topography and stream valley. In a comprehensively

instrumented gas well study case, Zhang and Su (2021) investigated how geological factors can influence the stability of shale gas wells in longwall chain pillars under shallow cover. The study concluded that horizontal movements over longwall chain pillars are also affected by coal seam and overburden dip as well as friction coefficients at interfaces. With a one degree of dip away from chain pillars, about one centimeter of additional maximum horizontal displacement could be induced along the gas well. High horizontal movement can occur near a stream valley where claystone layers are saturated and both frictional coefficient and normal pressure on the weak interface are low. Zhang et al. (2022) reported a case in which a casing deformation of 8.2 cm occurred at a 51-m depth in a gas well near a stream valley under shallow cover. The #1 mine-by case in this study also demonstrates that casing deformation could occur in uncemented production casing if a gas well is at a stream valley under shallow cover.

The occurrence and the amount of casing deformation also depends on gas well setback distance and the open annulus between the production and intermediate casings. For gas wells in chain pillars, setback distance is constrained by the economical size of the chain pillars. The optimal gas well location within chain pillars largely depends on overburden depth (Zhang et al. 2023b). Unconventional shale gas wells have a typical annulus of 8.47 cm between production and intermediate casing. All the three mine-by cases in this study show that the maximum longwall-induced deformation in the intermediate casing is less than 8.47 cm. Many conventional wells use 17.78-cm diameter production casing, and the annulus between production and intermediate casing can be as small as 5 cm.

6. LIMITATIONS

The findings in this paper are based on three gas well mine-by cases in the Pittsburgh coal seam with site-specific overburden geology and mining conditions. Casing deformations are affected by many factors. Casing deformations in uncemented production casings could potentially occur due to presence of a stream valley, existence of very thick massive strata, larger strata dip, and existence of weak claystone floor. The overburden depth in this study does not represent all deep cover cases in the Pittsburgh seam. Under deep cover, deformations in uncemented production casings could occur at the coal seam horizon, and this concern needs to be further addressed.

7. CONCLUSIONS

This paper presented three mine-by cases with gas wells in longwall chain pillars. Production casing deformations were measured by a multi-finger caliper and predicted using the FLAC3D modeling technique. Important conclusions from this study are made as follows:

- Casing deformations above the coal seam horizon are caused by longwall-induced horizontal displacement at the weak/strong rock interfaces.
- The casing cementing alternative is an effective means to minimize or eliminate production casing

deformations for the gas wells in longwall chain pillars under different depths of cover.

- An annulus of 8.47 cm between production and intermediate casings can usually uncouple production casing from longwall-induced stresses and deformations. Small production casings may not affect casing integrity.
- Casing deformation could potentially occur in uncemented production casing if the gas well is at a stream valley under shallow cover.
- With uncemented production casing, no casing deformation has occurred at the coal seam horizon up to 311 m overburden depth. But under deeper cover, a casing deformation could occur at the coal seam horizon if a weak claystone layer is present above or below the coal seam.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

ITASCA Consulting Group, Inc. 2017. FLAC-3D, Version 6.0, User's Guide.

Su, D.W.H., Zhang, P., Dougherty, H., Van Dyke, M., Minoski, T., Schatzel, S., Gangrade, V., Watkins, E., Addis, J., and Hollerich, C. 2019. Longwall-induced subsurface deformations and permeability changes – Shale gas well casing integrity implication. In *Proceedings of the 38th International Conference on Ground Control in Mining*. Morgantown, WV: West Virginia University, pp. 49–59.

Su, D.W.H., Zhang, P., Van Dyke, M., and Minoski, T. 2018. Effects of longwall-induced subsurface deformations on shale gas well casing stability under deep covers. In *Proceedings of the 37th International Conference on Ground Control in Mining*. Morgantown, WV: West Virginia University, pp. 63–70.

Su, D.W.H. 2017. Effects of longwall-induced subsurface deformations on the mechanical integrity of shale gas wells drilled over a longwall abutment pillar. *2017 SME Annual Meeting*, Feb.19-22, 2017, Denver, CO. Preprint 17-051, pp. 1-6.

Su, D.W.H. 2016. Effects of longwall-induced stress and deformation on the stability and mechanical integrity of shale gas wells drilled through a longwall abutment pillar. In *Proceedings of the 35th International Conference on Ground Control in Mining*. Morgantown, West Virginia, pp. 119–125.

Zhang, P., Su, D., and Kim, B.H. 2023a. Effect of casing cementing alternative on shale gas well casing deformations induced by longwall mining. In *Proceedings of the 42nd*

International Conference on Ground Control in Mining. Canonsburg, Pennsylvania, July 25-27, 2023.

Zhang, P., Su, D., Van Dyke, M., and Kim, B.H. 2023b. A case study of shale gas well casing deformation in longwall chain pillars under deep cover. *57th U.S. Rock Mechanics Geomechanics Symposium*, Atlanta, GA, June 26-28, 2023, pp.9.

Zhang, P., Su, D., Kim, B.H., and Midler, E. 2022. Comparison of measured and modeled casing deformations of a test well in a longwall abutment pillar. *56th U.S. Rock Mechanics Geomechanics Symposium*, Santa Fe, NM, June 2022, pp.9.

Zhang, P. and Su, D. 2021. FLAC3D modeling evaluation of the comprehensive NV-35 gas well pillar study. In *Proceedings of the 55th US Rock Mechanics/Geomechanics Symposium*, 20–23 June 2021. Texas.

Zhang, P., Dougherty, H., Su, D., and Trackemas, J. 2019. Influence of longwall mining on the stability of gas wells in chain pillars. In *Proceedings of the 38th International Conference on Ground Control in Mining*, Morgantown, West Virginia, pp. 38–48.