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ORIGINAL PAPER

A Case Study of Shale Gas Well Casing Deformation in Longwall Chain Pillars Under Deep Cover

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Abstract
Shale gas wells located in longwall chain pillars are subject to longwall-induced subsurface ground movements. Longwall mining on either side of the chain pillars can induce deformations in gas well casings. Excessive casing deformations could diminish casing integrity so that intrusive shale gas might leak into the longwall mine jeopardizing mine safety. This study investigated longwall-induced casing deformations of eight shale gas wells in the chain pillars between two adjacent longwall panels in the Pittsburgh coal seam under a cover depth of 314 m. The casing deformations were measured with a 56-arm caliper after each longwall face passed the gas well pad. Casing deformations were detected at ten locations below the surface after first panel mining, and the maximum casing deformation of 1.27 cm occurred at a 184-m depth. After second panel mining, the caliper survey showed that casing deformation locations remained the same, but generally the deformations increased slightly. The maximum deformation at the 184-m depth increased from 1.27 to 1.5 cm. The eight shale gas wells were also modeled by the FLAC3D modeling technique. The casing deformations predicted by the FLAC3D model were compared with the caliper survey results. The modeling predictions were in a good agreement with the caliper measurements in terms of deformation level and locations. The modeling results suggested that the gas well setback distance to the longwall gob would affect casing deformations, and that casing deformations can be minimized if gas wells are located around the center of the abutment pillar. The study showed that longwall-induced casing deformations occur at the same weak/strong rock interfaces after both first and second panel mining. The study also showed that, under deep cover, casing deformations above the coal seam horizon are smaller than those under shallow cover. Under deep cover, the production casing deformations evaluated in this study were demonstrated to be minimized by locating gas wells at the center of the chain pillars and by leaving the production casing uncemented from the surface to below the coal seam.

Highlights

- Casing deformations of a shale gas well in longwall chain pillars under deep cover were measured with a multi-finger caliper and predicted by the FLAC3D modeling.
- The measured casing deformations above the coal seam horizon were less than 1.27 cm after first panel mining and less than 1.50 cm after second panel mining.
- Longwall-induced casing deformations occur at the same weak/strong rock interfaces after both first and second panel mining.
- Under deep cover, casing deformations above the coal seam horizon are smaller than those under shallow cover.
- Under deep cover, production casing deformations can be minimized by locating gas wells at the center of the chain pillars and leaving the production casing uncemented from the surface to below the coal seam.

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1 Introduction

Gas wells drilled through coal seams have long been an issue for underground coal mining, and the recent development of shale gas wells in coal mining regions has raised more safety concerns when gas wells are in the vicinity of longwall mining (Mark and Rumbaugh 2020). In the eastern United States, abundant conventional gas wells have been drilled through the coal seams that are being actively mined by longwall mining. These conventional gas wells have less safety concerns because they are relatively shallow, and the gas pressure and volume are low. With the technology advances in horizontal drilling, shale gas wells have been drilled first vertically down and then horizontally into deeper and tight shale formations to retrieve gas through hydro-fracturing, and these gas wells are known as unconventional gas wells. Since 2003, over 1800 unconventional shale gas wells have been drilled through active and future Pittsburgh seam coal reserves in Pennsylvania, West Virginia, and Ohio (Su and Zhang 2023). Figure 1 shows the unconventional shale gas wells drilled in the longwall mining region in Pennsylvania. Unconventional shale gas wells have also been drilled in the coal reserves in the tristate region on the side of West Virginia and Ohio. These unconventional gas wells, whether tapped into the Marcellus or Utica formations, are drilled deeper and contain very high gas pressure and volume. For instance, Marcellus shale wells are 1500–2700 m deep, and gas pressure can be as high as 20 Mpa. Moreover, shale gas wells are drilled in clusters, and one well pad can house from a few wells up to 30–40 wells. The high pressure and high cost of shale gas wells create safety and economic concerns if they are influenced by longwall mining. 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 that jeopardizes underground miners' safety and health.

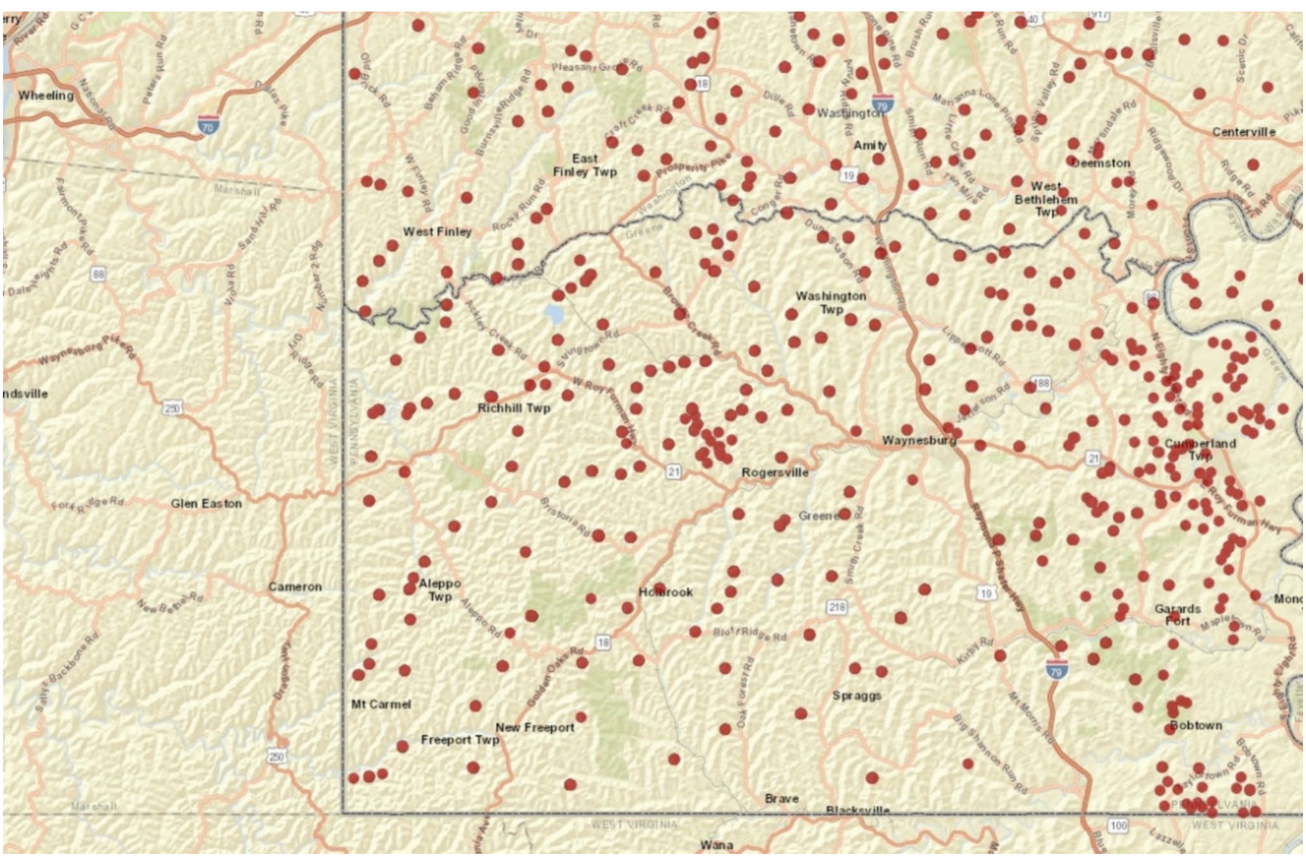

Fig. 1 Unconventional shale gas wells drilled in the longwall mining region in Pennsylvania (PA Oil and Gas Mapping <https://gis.dep.pa.gov/PAOilAndGasMapping/OilGasWellsStrayGasMap.html>)

Gas wells in longwall pillars are influenced by longwall mining. Figure 2 shows a typical panel layout of a U.S. longwall mining section (Peng 2006). The longwall panels are blocked out by development gate entries perpendicular to the main entries. The panel width varies from 300 to 500 m, and the panel length commonly ranges from 2500 to 4000 m. The gate entries are connected to the bleeder entries on both sides of the panels. The gate entries in the Pittsburgh coal seam consist of three entries. The development of gate entries and crosscuts forms chain pillars which are left in place after either side of the panel is mined. Longwall mining starts from the setup room and advances toward the recovery room. As the block of coal within a panel is progressively removed by longwall mining, the roof above the coal would cave and the overburden strata above would subside. Figure 3 illustrates how a gas well in a coal pillar is influenced by longwall-induced ground movements and abutment pressure. As shown in Fig. 3, longwall mining creates four zones in the overburden above the mined coal seam. As the overburden subsides, the rock layers also move laterally over the coal pillar adjacent to the longwall gob. If a gas well is located near the longwall gob, the relative horizontal movements along weak bedding planes could induce shear deformation in the gas well casings. Longwall mining also causes an increase in vertical stress or abutment pressure in the coal pillars as shown in Fig. 4 (Zhang et al. 2022c). The high abutment pressure causes pillar compression which can be transferred to gas well casings and induce

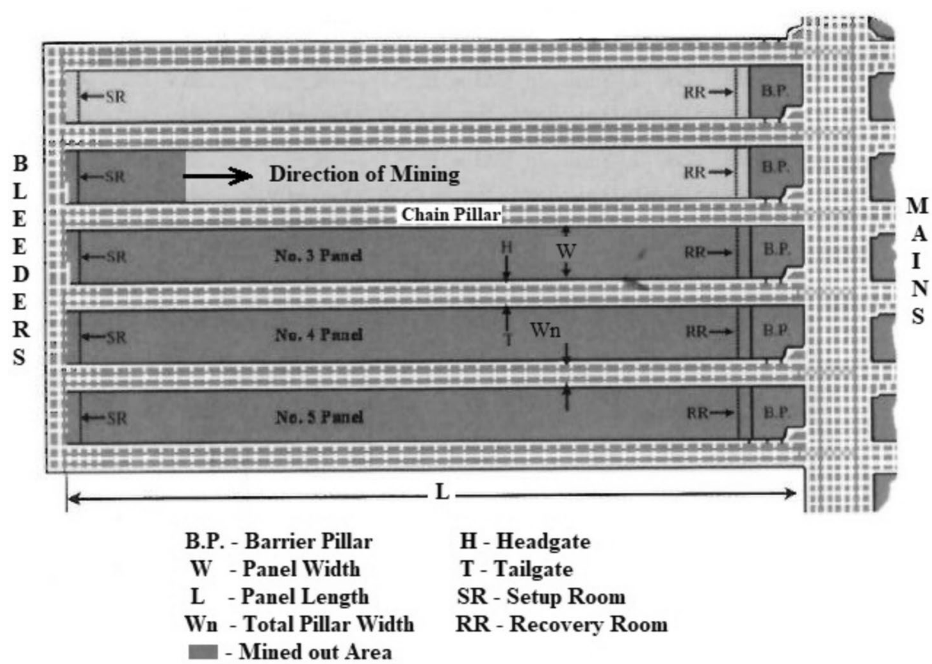

Fig. 2 A typical panel layout of a US longwall mining section (Peng 2006)

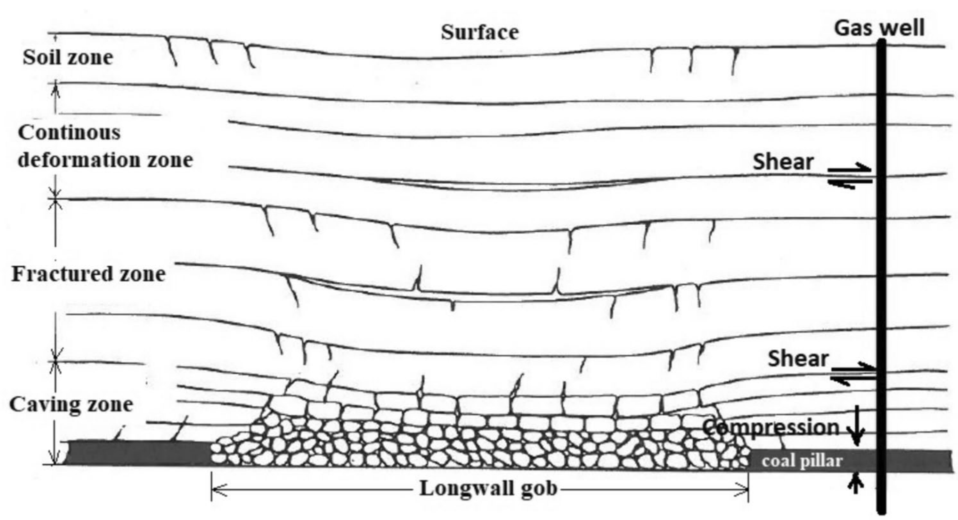

Fig. 3 Effects of longwall-induced subsurface ground movements on a gas well near the longwall gob

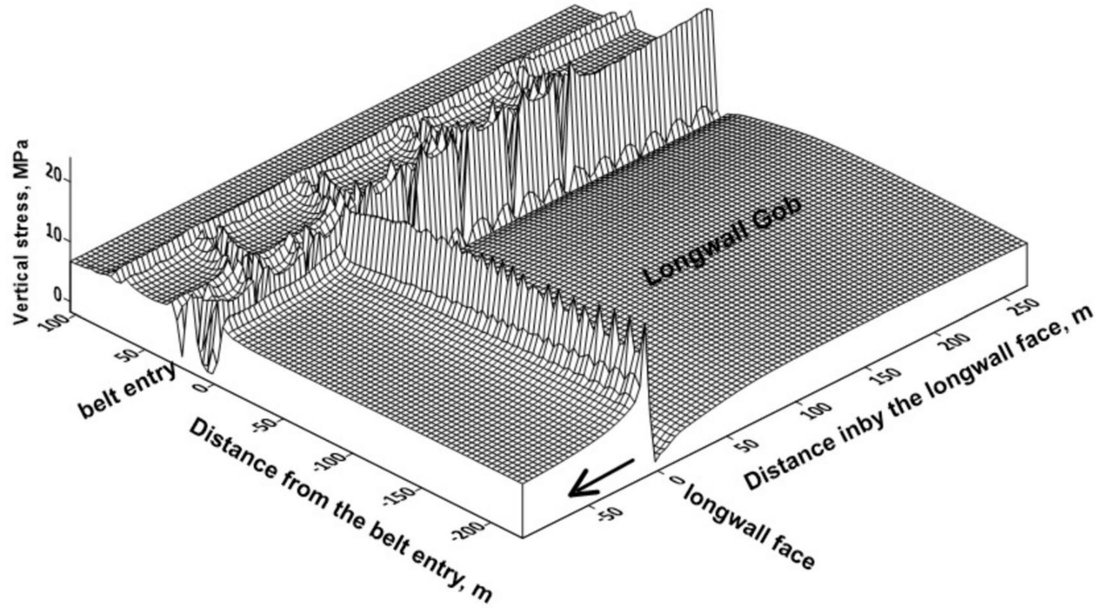

Fig. 4 Vertical stress distribution at the coal seam horizon adjacent to a longwall gob (Zhang et al. 2022c)

excessive stresses and deformations in the casings, potentially leading to a casing breach.

The current regulations for gas wells in longwall chain pillars are based on the 1957 Pennsylvania Gas Well Pillar Study (Commonwealth of Pennsylvania 1957). The study provided guidelines for gas well pillars by considering their support area, overburden depth, and the location of gas wells. The regulation also stipulates to place the gas wells in the center of the pillars penetrated by the wells. As the guidelines were developed for room-and-pillar mining under shallow cover, they are no longer applicable to modern longwall mining, particularly under deep cover. Failure instances have occurred even though the chain pillars for the gas wells met the requirements of the 1957 study. Zhang et al. (2021) re-analyzed the gas well failure cases from the 1957 gas well pillar study and modeled the stability of gas wells in both development pillars and longwall chain pillars. Results of this study indicated that the guidelines in the 1957 study may be appropriate for pillars protecting conventional gas wells in both room-and-pillar mining and longwall mining under overburden depths up to 213 m but may not be sufficient for protective pillars under deep cover.

If conventional gas wells are located close to longwall panels, the common practice is to plug the wells. Unconventional gas wells, however, are much more costly to be simply plugged. The gas wells within longwall chain pillars or barrier pillars may be left in place if the wells are protected by properly designed pillars and casings. For the safety of underground coal mines, the impact of longwall mining on the unconventional shale gas wells must be carefully evaluated before they are approached by longwall mining. Therefore, it is necessary to quantify longwall-induced subsurface movements and casing deformations. This paper presents a detailed case study of longwall-induced casing deformations of shale gas wells in longwall chain pillars in the Pittsburgh coal seam under deep cover.

Gas wells in the U.S. coal fields, whether active or abandoned, have caused many issues for longwall mining. But few previous studies have been published about gas well coal pillars in longwall mines. In 2003, Peng et al. (2003) published a study about two cases of conventional gas wells in longwall chain pillars: one damaged and one successful. A three-dimensional finite element model was developed to analyze the stability of the gas wells in longwall chain pillars. The study concluded that the gas well was damaged by the excessive vertical deformation in the claystone layer in the floor under longwall-induced abutment pressure. The study also concluded that a weak rock layer existing in the roof or floor near the coal seam horizon was an important factor in potentially causing gas well failure.

A few recent studies on unconventional gas wells in longwall pillars were conducted by Liang et al. (2014, 2017) and Wang et al. (2013). Based on numerical modeling of hypothetical cases, these studies recognized that casing deformations could be potentially caused by horizontal slips along weak bedding planes and that thick beds and surface slopes would affect the amount of deformation. But without field measurement data, these modeling studies could not go beyond qualitative analysis.

More recent studies on unconventional shale gas wells in longwall pillars have been published by Su (2016, 2017), Scovazzo (2018), and Scovazzo and Moran (2016). In 2012, in response to concerns surrounding unconventional gas wells and upon recognizing that the 1957 study was formulated without data from modern-day longwall mining, the Pennsylvania Department of Environmental Protection (PADEP) initiated a call for research to update the outdated regulation. In 2013 and 2014, a comprehensive gas well pillar study was conducted by a coal company and a few gas companies to collect data on subsurface deformations and the performance of gas well casings in longwall chain pillars. This was the first instrumentation study on gas well stability in longwall chain pillars in the Pittsburgh seam. The study was conducted in a southwestern Pennsylvania longwall mine under shallow cover of 184 m to evaluate the effect of subsurface strata movements on the gas well casings above the mining horizon. Four test wells were drilled in the abutment pillar between two longwall panels, and casing deformations were measured with inclinometer and multi-finger caliper. The results published by Su (2016, 2017) and Scovazzo (2018) showed that: (1) casing deformations were identified in two settings: at the weak/strong rock interfaces and within the Pittsburgh coal seam horizon; (2) casing deformations were in response to ground movements occurring at weak/strong rock interfaces and were above the well intersection with the angle of draw; (3) the most significant movement was found at the weak/strong rock interface on top of Limestone D stratum with relative horizontal movements in all the four test wells less than 5.8 cm.

In 2016, the National Institute for Occupational Safety and Health (NIOSH) initiated a shale gas well stability project to quantify subsurface deformations above, within, and below longwall abutment pillars under different overburden depth and to provide critical scientific data for assessing the stability of shale gas wells drilled through coal seams. NIOSH researchers have conducted additional instrumentation studies on test wells under different overburden depths and also measured casing deformations in actual shale gas wells in longwall chain pillars.

Two instrumentation studies on gas wells in longwall chain pillars under shallow cover were published by Su et al. (2019a) and Zhang et al. (2022b). In each study, one test well was drilled in the abutment pillar between two longwall panels in the Pittsburgh coal seam, and casing deformations were measured with an inclinometer or a 60-arm caliper. Both studies showed that under shallow cover, especially under the influence of a major stream valley, longwall-induced subsurface deformations were higher than those detected under deep cover.

In addition to the instrumentation studies under shallow cover, one deep-cover instrumentation study was published by Su et al. (2019b). The longwalls extracted 457-m-wide panels under 361 m of cover in the Pittsburgh seam. One 198-m-deep, in-place inclinometer monitoring test well was drilled and installed over a 46-m by 84-m centers abutment pillar. The study found that under deeper cover, longwall-induced subsurface deformations were smaller than those observed under shallow cover, although longwall-induced vertical stress was higher at and below the coal seam level.

Along with the instrumentation study, Su (2017), using the calibrated ABAQUS model, further investigated the effect of overburden depth and a cementing alternative on longwall-induced stresses and deformations in gas well casings. Su (2017) showed 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. He illustrated that leaving the production casing uncemented from 15 m below the coal seam to the surface can effectively uncouple the production casing from longwall-induced stresses and deformations.

To further investigate how deep cover affects longwall-induced shale gas well integrity, researchers from the National Institute for Occupational Safety and Health (NIOSH) recently conducted a study on actual shale gas wells located in longwall chain pillars under deep cover. This study concerns the influence of longwall mining on eight shale gas wells in a shale gas well pad located in the chain pillars between two adjacent longwall panels under an overburden depth of 314 m. FLAC3D modeling was performed to predict longwall-induced casing deformations in one of the gas wells based on site-specific mining and geological conditions. A 56-arm caliper survey was performed on the well to measure the longwall-induced intermediate casing deformations after each panel on either side of the chain pillars was mined. The first panel passed the shale gas well pad in October 2021, and the caliper survey was conducted about a month after the mine-by. The results of measurements and modeling for first panel mining were studied by Zhang et al. (2022a). The study found that casing deformations occurred at ten locations below the surface, and the maximum casing deformation was less than 1.3 cm. The second panel mine-by was in August 2022. This paper presents the results of the multi-finger caliper survey and FLAC3D modeling for second panel mining. The established model is also used to analyze the optimal pillar layout and gas well location under deep cover. The casing deformations measured from this case are also compared with the measurements from other cases to demonstrate that a casing cementing alternative by leaving production casing uncemented can generally eliminate production casing deformations.

This is the first case study on multiple unconventional shale gas wells in longwall chain pillars under deep cover. It was expected from the previous studies [Su 2017; Zhang et al. 2022b, 2023a, b) that the casing deformations above the mining horizon in this case would occur at the same locations as those after first panel mining and the amount of deformation would increase slightly after second panel mining. Since the overburden depth in this case is deep, it is possible that casing deformation could occur at the coal seam horizon. Although the chain pillars had a stability factor of 1.79 under isolated loading (Mark and Agioutantis 2018), deformations in the coal pillar after second panel mining could induce high stress in the casings. Because of the concerns of potential casing deformations at the near-seam horizon in this case, the pillar pressure at the gas well, longwall-induced stresses in the casings, and the measured casing diameter changes at the near-seam horizon after second panel mining are carefully investigated.

2 Mining and Geological Conditions at the Study Site

The study site consists of a shale gas well pad with eight shale gas wells located in the chain pillars between two adjacent longwall panels in the Pittsburgh coal seam. Figure 5 shows the panel layout and shale gas well pad location. The longwall panels are developed with a three-entry system with a total chain pillar width of 66 m center-to-center. The longwall panels are 480-m wide with a mining height of 2.1 m. The overburden depth at the well pad is 314 m. Figure 5 also shows the surface topography around the gas well pad. The gas well pad is located near the top of the hill. The elevation contour lines show that the surface at the well pad dips toward a valley on the northeast side. The elevation difference is about 46 m between the well pad and the bottom of the valley.

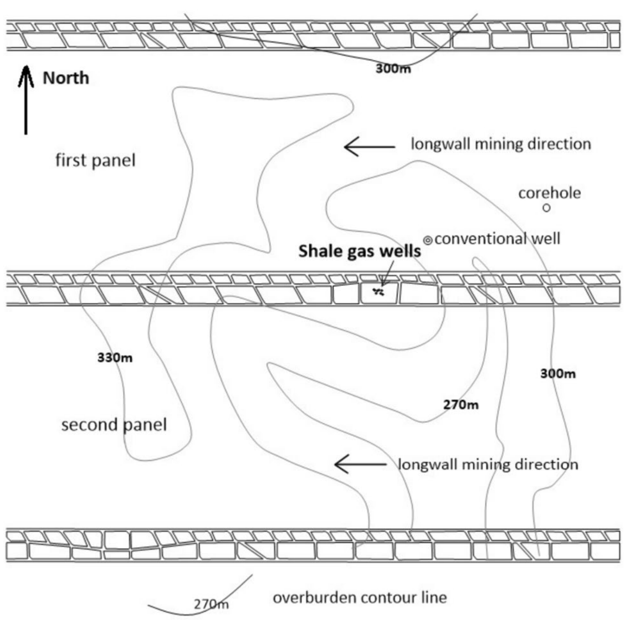

Fig. 5 Longwall panel layout and shale gas well pad location

Figure 6 shows the gas well pillar layout. Eight shale gas wells are located around the center of an abutment pillar of 45.7-m width (rib-to-rib). Because of the stability concerns influenced by longwall mining, these gas wells were planned to be plugged before the first longwall panel approached. The production casings in all the wells were uncemented and were pulled out before first panel mining. Eventually, seven gas wells were plugged but one well, as shown in red in Fig. 6, was left unplugged for the caliper survey. This well was surveyed with a 56-arm caliper after first and second panel mining for longwall-induced casing deformations. The setback distance of the surveyed gas well is 33 m to the first panel gob and 29.3 m to the second panel gob.

The overburden geology at the gas well site is determined by correlating the core log with the gamma log. The core log is from the nearest corehole about 305 m away on the eastern side of the well pad, and the gamma log is from a gas well about 152 m from the well pad. The locations of the corehole and the gamma-logged gas well (labeled as conventional well) are shown in Fig. 5. According to the core log, the overburden consists of shale, sandy shale, claystone, limestone, and sandstone. Figure 7 shows gamma logs and weak interface locations. Weak interfaces include weak claystone layers and coal seams. The weak claystone layers are identified from the gamma logs, and the coal seams are identified from the core log. Four main coal seams are present above the Pittsburgh coal seam. The weak interfaces, representing the weak beddings between a weak layer and a relatively strong massive strata, are implemented in the FLAC3D model.

3 FLAC3D Model for Gas Wells in Longwall Chain Pillars

To evaluate the influence of longwall mining on shale gas wells in longwall chain pillars, NIOSH researchers have developed FLAC3D modeling techniques to predict

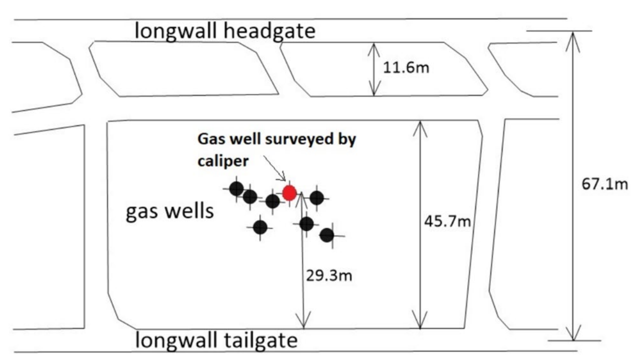

Fig. 6 Gas well pillar layout

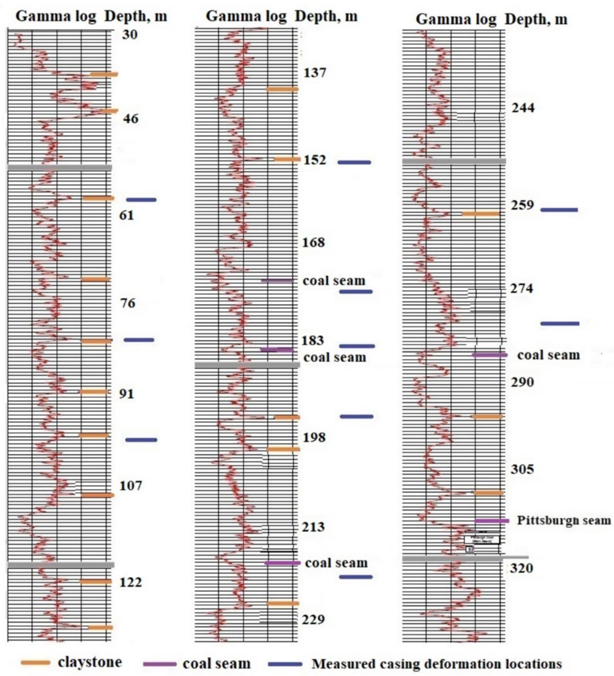

Fig. 7 Gamma logs and weak interface locations

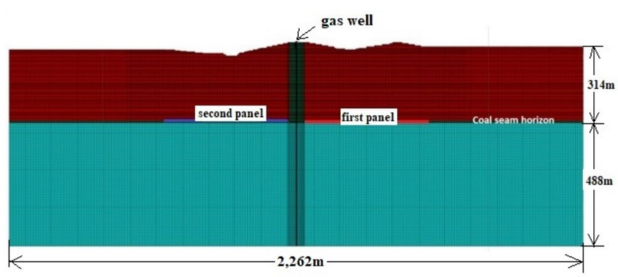

Fig. 8 Cross-sectional view of the FLAC3D model

longwall-induced stresses and deformations in gas well casings and the surrounding strata (Su and Zhang 2023; Su et al. 2019b; Zhang et al. 2019, 2020, 2022a, 2023b; b; Tulu et al. 2017); ; , ; ; . In this study, a FLAC3D model (Itasca 2021) was set up based on the site-specific geological conditions and longwall mining layouts around the shale gas well pad. Figure 8 shows the cross-sectional view of the FLAC3D model. The model included overburden from the Pittsburgh coal seam to the surface, two longwall panels, and eight gas wells in the well pad. The overburden lithology was based on the nearest corehole about 305 m from the gas well pad. Table 1 shows the rock properties used in the model. The weak bedding interface locations were based on the gamma logs from the nearest gas well about 152 m from the well pad. The interfaces were modeled with a cohesion of 0.14 MPa and a frictional coefficient of 0.2. Surface slope over the longwall panel was also modeled. The longwall caving zone, three times the mining height from measurements, was modeled by strain-hardening material implemented by the "FISH" scripting language. The overburden strata above the caving zone were modeled with ubiquitous joint materials, and the coal seam, immediate roof, and floor were modeled with Mohr–Coulomb materials (Su et al. 2019b; Zhang et al. 2020); . In situ horizontal stresses were applied in the model with a maximum horizontal stress three times the vertical stress along the face advance direction and a minimum horizontal stress two times the vertical stress across the face advance direction.

Each of the eight gas wells were constructed with four casings with their specifications shown in Table 2. Two casings were fully cemented through the Pittsburgh coal seam. The surface casing was fully cemented from the surface to a 434-m depth, and the intermediate casing was fully cemented from the surface to a 1051-m depth. The production casing was uncemented through the Pittsburgh seam and was pulled out before first panel mining. The intermediate and surface casings for all eight gas wells were modeled according to their construction and specifications. The

Table 1 Rock properties used in the model

Rock type	Young's modulus, MPa	Poisson's ratio	Cohesion, MPa	Internal friction angle, degrees	Tensional strength, MPa
Coal	2,070	0.30	1.9	28	0.3
Claystone	2,900	0.30	1.9	28	0.3
Shale	11,600	0.25	11.7	35	4.5
Sandy shale	11,600	0.25	11.7	35	4.5
Sandstone	11,600	0.25	17.9	35	6.9
Limestone	17,400	0.22	15.9	35	6.1
Shaly limestone	17,400	0.22	14.5	38	5.9
Shaly sandstone	15,000	0.22	11.7	38	4.8
Silty shale	11,600	0.25	11.7	32	4.2

Table 2 Casing construction of the gas wells

Casing type	Outside diameter, cm	Casing weight	Casing grade	Casing thickness, cm	Installed from	To depth, m	Top of cement (TOC), m
Conductor	51				Surface	12	Surface
Surface casing	34.0	54.5#	J-55	0.97	Surface	434	Surface
Intermediate casing	24.4	40#	MC-50	1.0	Surface	1051	Surface
Production casing	14.0	20#	P-110	0.92	Surface	5058	1976

conductor casing was not modeled because it went only 12-m deep and had little effect on casing deformations at deeper depths. Figure 9 shows the construction of the gas well casings in the model and casing specifications. Since the production casing was pulled out before the first panel mine-by, the production casing was not included in the model. The intermediate casing in well #5 was surveyed by a 56-arm caliper. The steel casings were modeled with von Mises material, and the cement fillings were modeled with Mohr–Coulomb material (Zhang et al. 2023b; Zhang et al. 2020); . The casings were installed in the model before the longwall gate entries were developed. Table 3 shows the mechanical properties of the modeled shale gas well casings.

The FLAC3D model setup for the study site was verified with surface subsidence and pillar stress as their measurements in similar mining conditions in the Pittsburgh seam are available for comparison. Figure 10 shows predicted and measured final surface subsidence across the gas well and longwall panels after each panel is mined. The predicted final subsidence curve is almost flat around the panel center but is asymmetrical due to the presence of surface slope. The model predicts a maximum subsidence of about 1.3 m around the panel centers. At the gas well location, the predicted surface subsidence is about 6.4 cm after first panel mining and about 25 cm after second panel mining. The measured surface subsidence for comparison is from a subsidence survey on an adjacent longwall panel with similar mining conditions and overburden depth.

Figure 11 shows the predicted vertical stress distribution across the chain pillars at the coal seam horizon. At the coal seam level, the gas well is mainly influenced by the longwall-induced vertical stress in the coal pillar near the gas well. The predicted pillar pressure increase at the gas well is about 3 MPa after first panel mining and about 9 MPa after second panel mining. In comparison with the measured pillar pressure increase under similar overburden depth by Su et al. (2019b), the model reasonably predicts the longwall-induced vertical stress across the chain pillars.

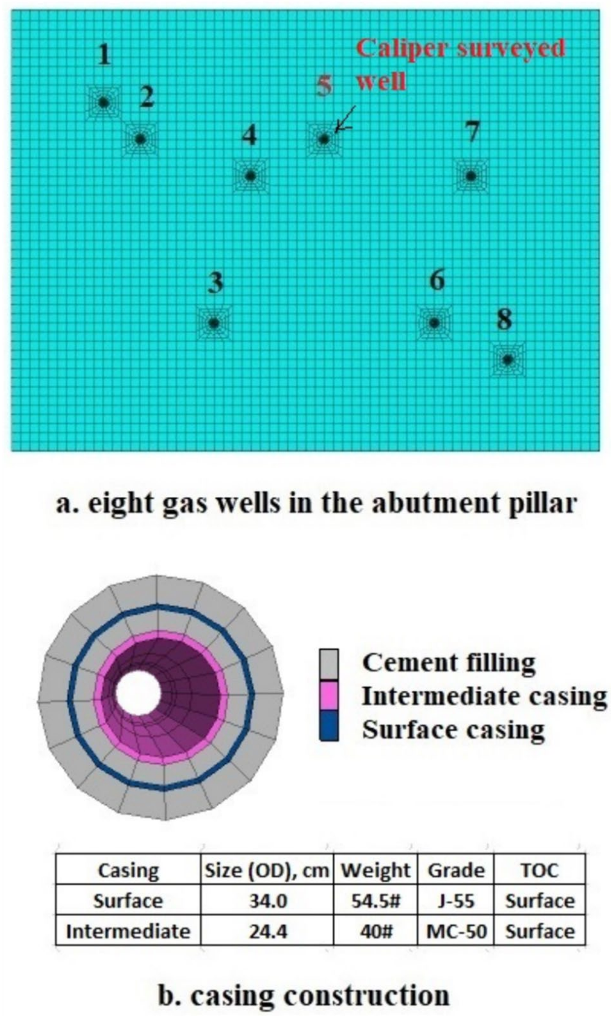

Fig. 9 Zoomed-in plane view of the eight gas wells in the model and casing specifications

Table 3 Mechanical properties of the modeled shale gas well casings

Casing type	Outside diameter, cm	Wall thickness, cm	Young's modulus, MPa	Poisson's ratio	Yield strength, MPa
Surface casing	34.0	1.0	2.0×10^5	0.3	379.3
Intermediate casing	24.4	1.0	2.0×10^5	0.3	379.3
Production casing	14.0	0.9	2.0×10^5	0.3	758.6
Cement			4800	0.3	20.0

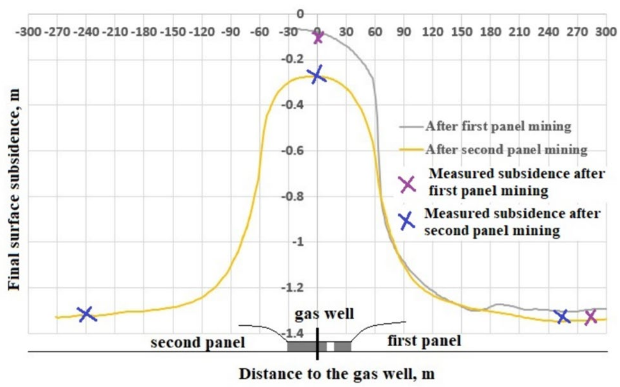

Fig. 10 Predicted final surface subsidence across the chain pillars after first and second panel mining

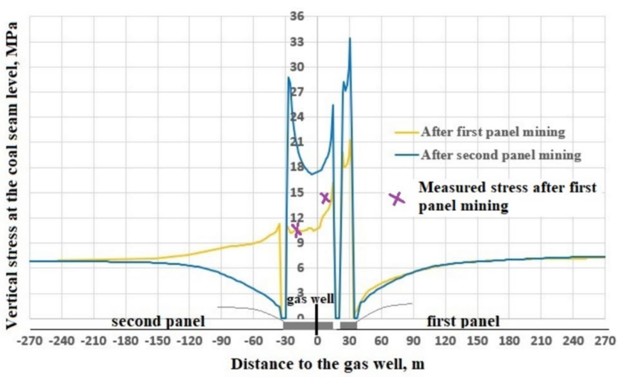

Fig. 11 Predicted vertical stress distribution across the chain pillars at the coal seam horizon

4 Longwall-Induced Deformations in the Intermediate Casing After First Panel Mining

The established model was used to predict casing deformations before each panel was mined by the well pad, and the predicted casing deformations were later compared with the measurements after the well was surveyed. The model predicted horizontal displacement along the intermediate casing in well #5 after first panel mining as shown in

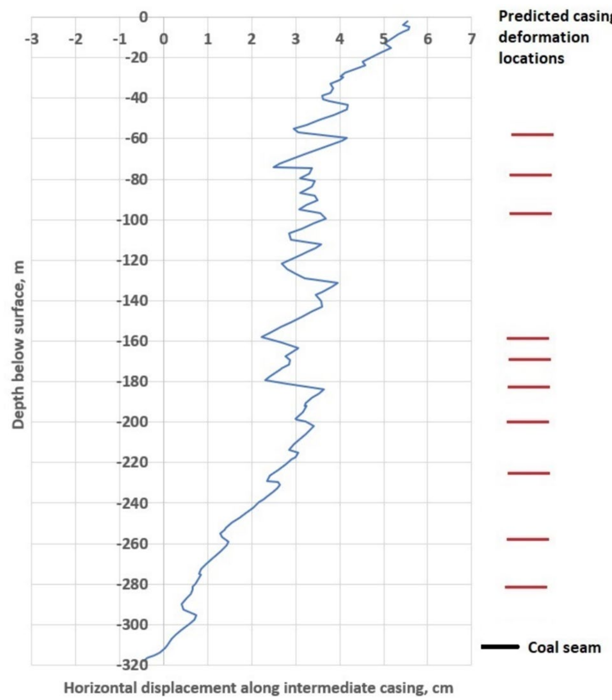

Fig. 12 Predicted horizontal displacement along the intermediate casing in well#5 after first panel mining

Fig. 12. With first panel mining, the casing moves toward the first panel gob. At the surface, the casing moves about 5.5 cm toward the gob. In the overburden, the casing is subject to relative horizontal displacements or shear displacements at the interface locations. Casing deformations are caused by relative horizontal displacements or shear displacements along strong/weak rock interfaces. Based on the horizontal displacement curve, the locations of casing deformations are predicted as shown in Fig. 12. Since the relative horizontal displacements at the interfaces are small, the casing deformations are also small. The small relative horizontal displacements under deep cover can be attributed to high frictional resistance along the interfaces under high abutment pressure (Su and Zhang 2023; Zhang et al. 2023b); .

The intermediate casing deformations were measured with a 56-arm caliper after first panel mining. The caliper survey measures the inside casing diameter and gives the locations and magnitudes of casing deformation. Figure 13 shows the measured and predicted minimum casing inside diameters along the intermediate casing. Casing deformations are detected at ten locations below the surface. The horizontal axis of the figure shows the inner diameter of the intermediate casing, and for the 9–5/8-in 40# MC-50 casing, the nominal inner diameter is 22.44 cm. Any deviation from this nominal diameter indicates casing deformations. The measured maximum deformation is less than 1.5 cm. As shown in Fig. 13, the predicted casing deformations generally match with the measurements in terms of deformation location and magnitude. By comparing the measured deformation locations with the overburden geology in Fig. 7, it appears apparent that all the casing deformations occur at the weak claystone or coal interfaces.

Figure 14 shows a 3D view of the casing deformation at the depth of 184-m visualized using caliper measurement data. It shows that the casing deforms at two opposite sides due to horizontal shearing along the interface. According to the gamma logs, the deformation occurred at a coal seam interface. As the casing deformation is induced by shear displacement at the coal interface, the extent of the deformation along the casing is limited within the coal thickness by about 0.46 m.

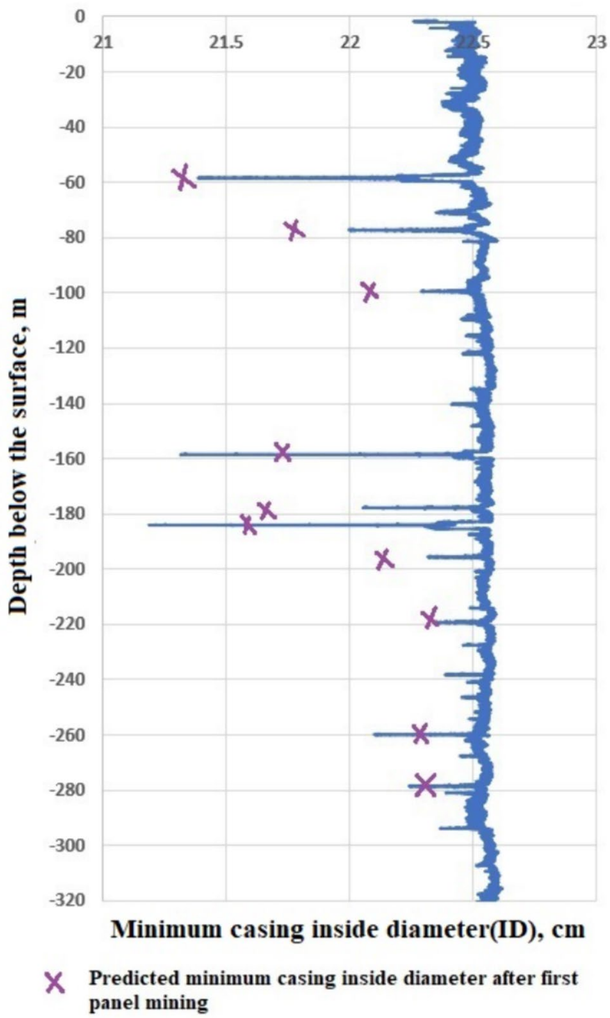

Fig. 13 Measured minimum inside diameters along the intermediate casing in well#5 after first panel mining

5 Longwall-Induced Deformations in the Intermediate Casing After Second Panel Mining

After second panel mining, the casing moves toward the second panel gob. Figure 15 shows the predicted horizontal displacement along the intermediate casing in well #5. The casing deformations, as determined by the relative horizontal displacements at the interface locations, are predicted to occur at the same locations as those after first panel mining. Casing deformations induced by second panel mining are accumulative and are reflected by the changes of relative horizontal displacement after both panels are mined. The predicted incremental relative horizontal displacements and casing diameter reductions are shown in Table 4. It shows that longwall-induced incremental casing deformations by second panel mining are much smaller than those by the first panel mining.

The intermediate casing deformations in well #5 were also measured with a 56-arm caliper after second panel mining. Figure 16 shows the measured minimum casing inside diameters along the intermediate casing. The figure

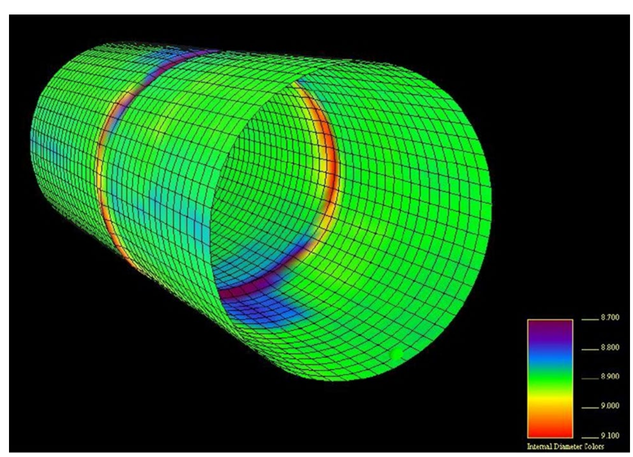

Fig. 14. 3D view of the casing deformation at a 184-m depth after first panel mining

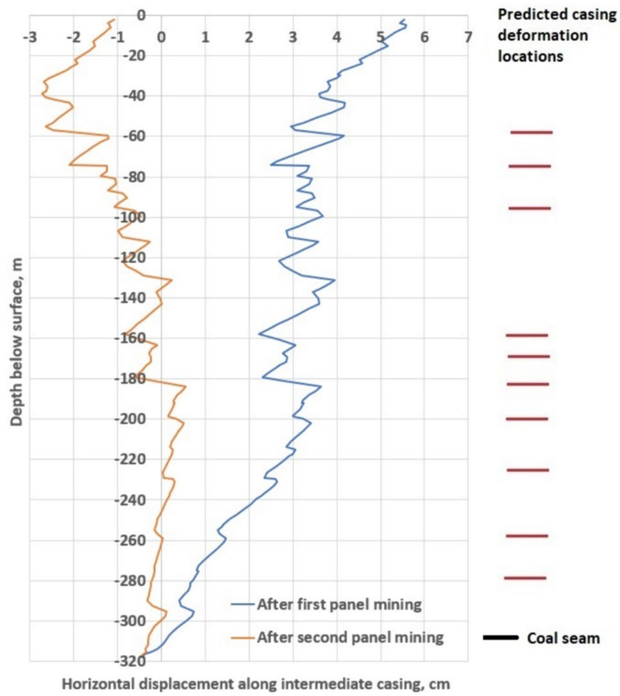

Fig. 15 Predicted horizontal displacement along the intermediate casing in well#5 after first and second panel mining

shows that the casing deformations after second panel mining occurred at the same locations as those after first panel mining but increased slightly at the major deformation locations. In this case, the largest deformation increased by 18%. This agrees with the previous studies by Su (2017), Zhang and Su (2021), and Zhang et al. (2022b): major casing deformations would increase about 20–30% with second panel mining.

Multi-finger caliper survey results showed that longwall-induced casing deformations caused by horizontal shear displacement occur on two opposite sides of the casing. This is also verified in the numerical model. Figure 17 shows the modeled casing deformation at a 184-m depth in well#5 after first and second panel mining. With a relative horizontal displacement at the interface, the casing deforms on two opposite sides with the casing center shifted slightly at the deformation horizon. The result of the caliper survey at the deformation location would be a combination of horizontal shifting and casing diameter reduction.

A comparison of predicted and measured casing deformations in the intermediate casing of well #5 is summarized in Table 4. The minimum casing diameter reduction is estimated from the predicted relative horizontal displacement multiplied by a factor of 1.4. This factor is determined according to the field measurement of casing deformations under shear displacement (Zhang et al. 2022b). Generally, the predictions are in good agreement with the measurements in terms of deformation level and location. A smaller amount of deformation increase is predicted and measured for second panel mining. This also agrees with the previous NIOSH findings in the studies by Su (2017) and Zhang et al. (2022b).

Intermediate casing deformations in other wells are also predicted from the model. Although the other seven wells were plugged, longwall-induced deformation would still occur in the intermediate and surface casings. With the given overburden geology at the gas well pad, casing deformations are dependent on setback distance, the location of the well relative to the longwall gob. Predicted horizontal displacements along the intermediate casings are compared for the wells with similar setback distances. Wells #1, #2, #4, #5, and #7 have about the same setback distance and are

Table 4 Comparison between predicted and measured casing deformations after first and second panel mining

Depth below surface, m	First panel mining			Second panel mining		
	Predicted relative horizontal displacement, cm	Predicted casing diameter reduction, cm	Measured casing diameter reduction, cm	Predicted incremental relative horizontal displacement, cm	Predicted casing diameter reduction, cm	Measured casing diameter reduction, cm
58	1.05	1.47	1.09	0.05	1.54	1.24
77	0.70	0.98	0.51	0.00	0.98	0.58
99	0.30	0.42	0.18	0.00	0.42	0.25
158	0.80	1.12	1.14	0.05	1.19	0.89
177	0.01	0.01	0.41	0.01	0.03	0.41
184	1.20	1.68	1.27	0.00	1.68	1.50
195	0.25	0.35	0.13	0.05	0.42	0.25
220	0.05	0.07	0.10	0.00	0.07	0.10
259	0.15	0.21	0.36	0.00	0.21	0.38
279	0.01	0.01	0.23	0.01	0.03	0.23

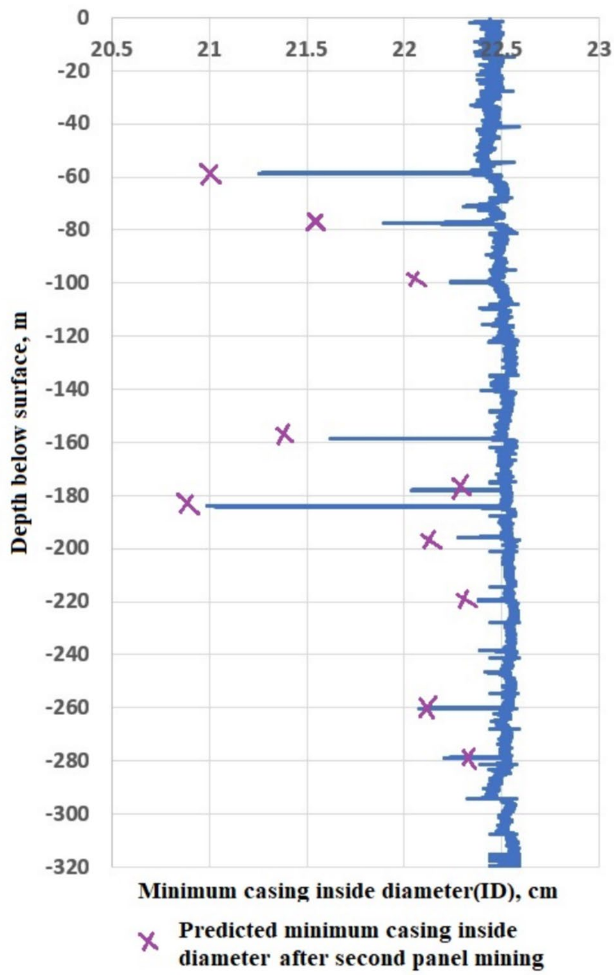

Fig. 16 Measured minimum inside diameters along the intermediate casing in well#5 after second panel mining

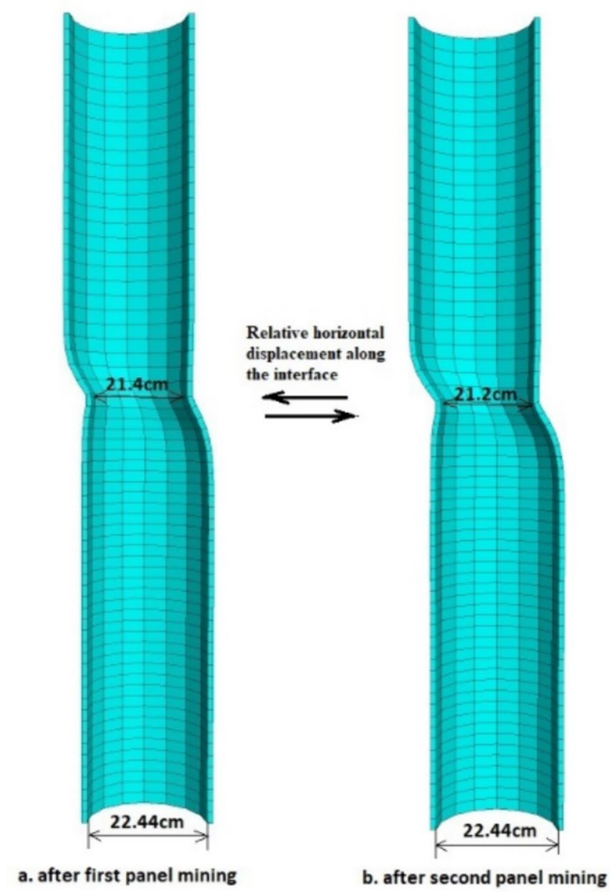

Fig. 17 Modeled casing deformation at 184-m depth after first and second panel mining

expected to have the same casing deformations. As shown in Fig. 18, the predicted horizontal displacements along the intermediate casings in wells #1 and #5 are about the same. The other three wells with similar setback distance are wells #3, #6, and #8. Figure 19 shows the predicted horizontal displacements along the intermediate casings in wells #3 and #8. The horizontal displacements along the intermediate casings in both wells are about the same. However, the horizontal displacements in these wells are different from those in the other five wells because of different setback distances. Table 5 shows a comparison of the predicted casing deformations between well #1 (the closest well to the first longwall gob) and well #8 (the closest well to the second longwall gob). It shows that longwall mining induces more casing deformations in well #1 than in well #8 after both first and second panel mining because well #1 is closer to the first longwall gob. Although second panel mining induces more incremental casing deformations in well #8 than in well #1, the accumulated total casing deformation after second panel mining in well #8 is less than in well #1. This suggests that gas wells in longwall chain pillars are subjected to smaller casing deformations if they are located around the center of the abutment pillar.

Casing deformations are affected by many factors such as overburden depth, surface topography, interface friction, presence of thick massive strata above and below the interface, and gas well setback distance from the longwall gob (Su and Zhang 2023; Zhang et al. 2023a); . To predict casing deformations using numerical modeling, it is important to obtain site-specific overburden geology and rock properties. In many cases, it is difficult to predict casing deformations to a high degree of accuracy but for general evaluation of the impact of longwall mining on gas wells, and it may be sufficient to know the deformation horizons and the maximum deformation level. As this study shows, the maximum casing deformation in the intermediate casing was 1.27 cm after first panel mining and 1.50 cm after second panel mining. With an annular space of 8.5 cm between the intermediate casing and production casing, leaving production casing uncemented would generally uncouple production casing

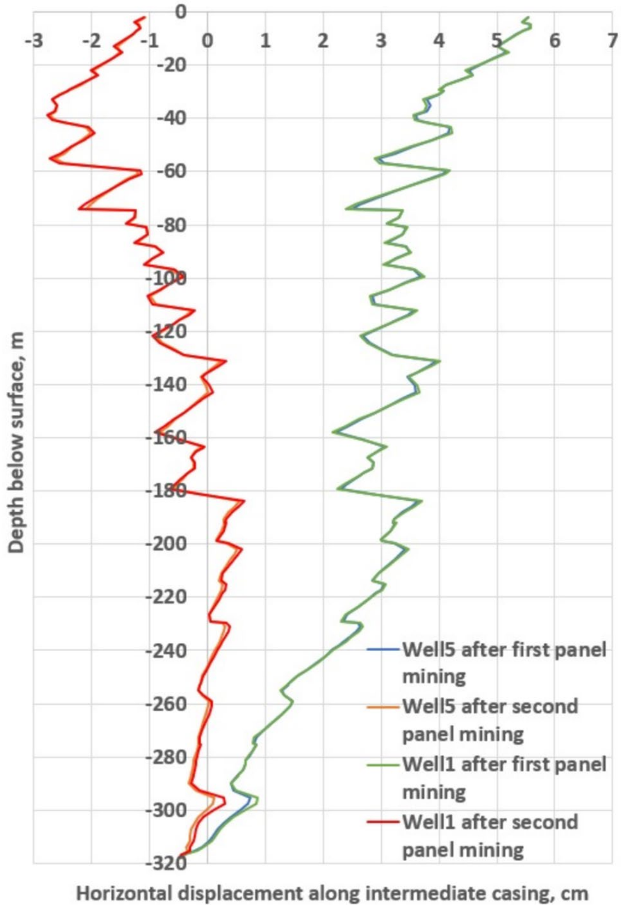

Fig. 18 Predicted horizontal displacements along the intermediate casings in wells #1 and #5

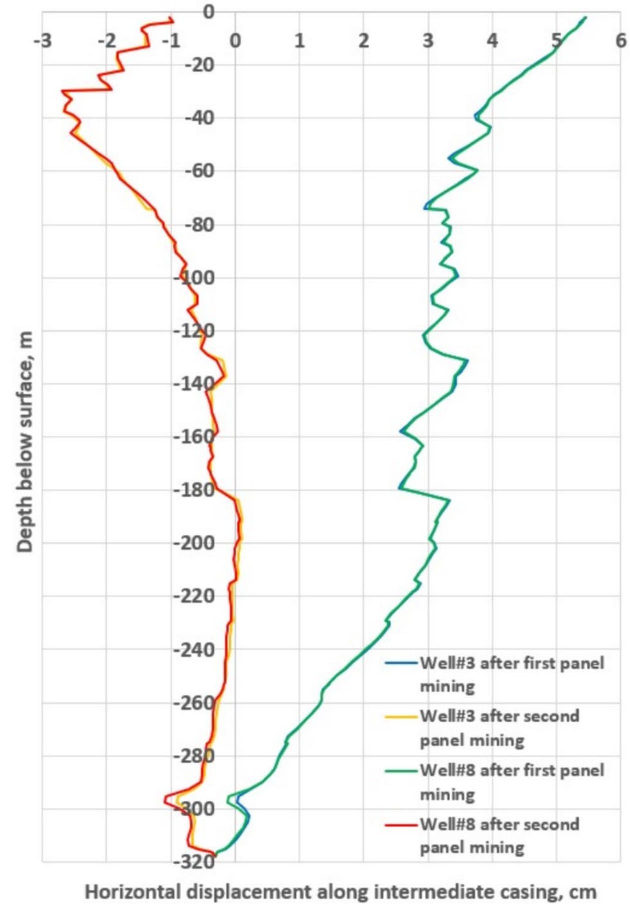

Fig. 19 Predicted horizontal displacements along the intermediate casings in wells #3 and #8

from longwall-induced deformations (Su and Zhang 2023; Zhang et al. 2023a); .

To demonstrate the effectiveness of uncemented production casing in minimizing production casing deformations, the maximum casing deformation in the current case is compared with the maximum measured casing deformations from five other mine-by cases. Figure 20 shows measured maximum casing deformations above the mining horizon from recent mine-by cases of gas wells in longwall chain pillars under different overburden depths (Zhang et al. 2022b, 2023b; Zhang and Su 2021). The deformation horizon at a depth below the surface is also labeled at each data point. The measured data show a general trend that the casing deformation level reduces with the increase of overburden depth. Under shallow and medium cover less than 250 m, the maximum deformation level is less than 8.2 cm. Under deep cover greater than 250 m, the maximum deformation level is less than 2.5 cm. The smaller casing deformation under deep cover is due to high abutment pressure and high frictional resistance along weak claystone interfaces. As the annulus between production casing and intermediate casing

Table 5 Comparison of predicted intermediate casing deformations between well #1 and well #8 after first and second panel mining

Depth below surface, m	Well #1		Well #8	
	After first panel mining	After second panel mining	After first panel mining	After second panel mining
58	1.47	1.54	0.56	1.12
77	0.98	0.98	0.28	0.56
99	0.42	0.42	0.14	0.28
158	1.12	1.19	0.52	0.66
177	0.01	0.03	0.01	0.02
184	1.68	1.68	0.70	1.20
195	0.35	0.42	0.04	0.05
220	0.07	0.07	0.07	0.15
259	0.21	0.21	0.05	0.10
279	0.01	0.03	0.01	0.01

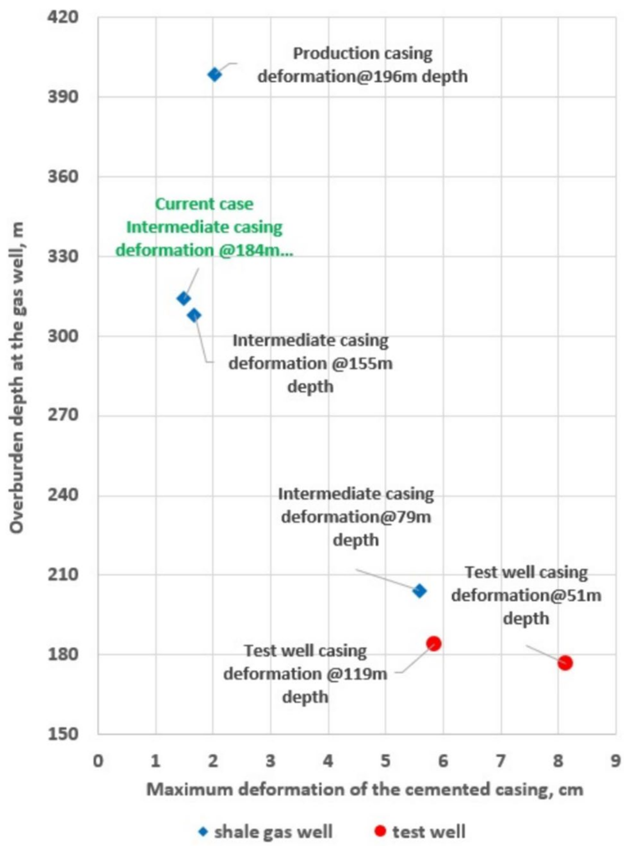

Fig. 20 Measured maximum casing deformations above the mining horizon from six recent mine-by cases of gas wells in longwall chain pillars under different overburden depths

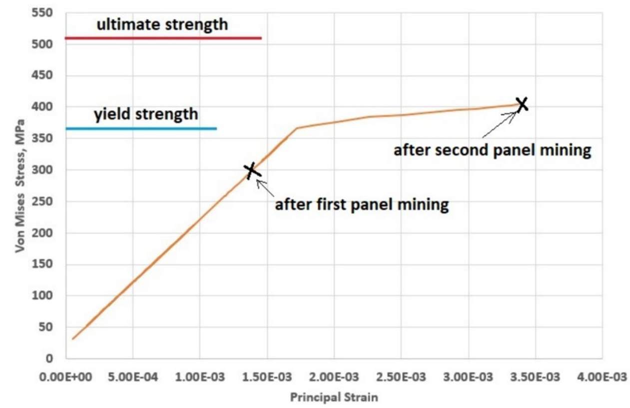

Fig. 21 Stress and strain developed in the intermediate casing in well#5at the coal seam after first and second panel mining

in typical shale gas wells is 8.5 cm, the maximum casing deformation levels as measured in the recent mine-by cases imply that a cementing alternative, by leaving production casing uncemented, can generally eliminate production casing deformations in the overburden over the coal seam horizon. The effectiveness of a casing cementing alternative has been demonstrated in a mine-by case in which five shale gas wells were passed by longwall mining and no deformations were detected in the uncemented production casings (Zhang et al. 2023a). All five shale gas wells resumed normal production after being temporarily plugged during the period of mine-by. With the effectiveness of the cementing alternative, most of the shale gas wells, especially recently drilled unconventional shale gas wells in the Pittsburgh Coal reserves, have been completed with uncemented production casings at least from 30 m below the coal seam to the surface. No wellbore stability and production issues have been reported of uncemented production casings.

Casing deformations in the overburden above the coal seam are mainly induced by relative horizontal movements along weak/strong rock interfaces. In the coal seam horizon, however, casing deformations could be caused by vertical compression due to high abutment pressure under deep cover. To investigate the potential casing deformations at the coal seam level, the stress and strain in the intermediate casing at the coal seam are obtained from the model. The zones of the casings around the coal seam are densified so that the stress and strain can be calculated more accurately. Figure 21 shows the stress and strain developed in the intermediate casing at the coal seam as each longwall panel is mined. The figure shows that longwall-induced von Mises stress in the intermediate casing at the coal seam is less than its yield strength after first panel mining. After second panel mining, the casing yields with small plastic strain developed in the casing. Since the stress in the casing has not reached its ultimate strength, no casing failure and large deformations are predicted from the model. To verify this result, the caliper survey data at the coal seam horizon are carefully examined for any potential casing deformations. Figure 22 shows the caliper-measured minimum intermediate casing inside diameters at the coal seam horizon after first and second panel mining. The charts show that the casing inside diameter changes little from after first panel mining to after second panel mining, thereby confirming that no casing deformations occurred in the intermediate casing at the coal seam. This case study suggests that for gas wells in longwall chain pillars, casing deformations may not occur at the coal seam under a cover depth up to 314 m if no weak claystone is present in the near-seam horizon because the longwall-induced stress level in the casing is less than its ultimate strength.

However, if a weak claystone is present in the near-seam horizon, casing deformations could possibly occur. A detailed analysis of the gas well failure cases from the 1957 Pennsylvania Gas Well Pillar Study by Zhang et al. (2021) showed that under overburden depth greater than 228 m, the gas wells in chain pillars could be damaged at the coal seam horizon even if the chain pillars around the gas wells meet

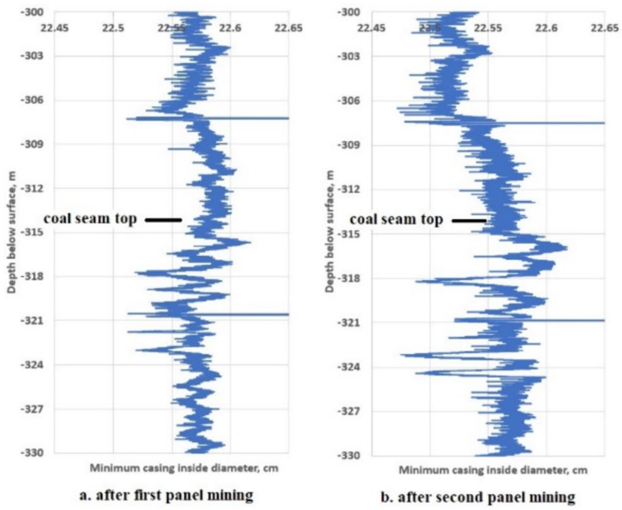

Fig. 22 Minimum intermediate casing inside diameters from the caliper survey showing that no deformation occurred at the coal seam horizon after first and second panel mining

the 1957 guidelines. In a case with a conventional gas well in longwall chain pillars under an overburden depth of 293 m, a large casing deformation occurred at the claystone floor 5 m below the coal seam after second panel mining. This case was studied by Luo et al. (1999), Peng et al. (2003), Scovazzo and Moran (2012), and Zhang et al. (2020). In a recent mine-by case with a shale gas well in longwall chain pillars under an overburden depth of 398 m, a large casing deformation occurred at the claystone roof 7 m above the coal seam after second panel mining (Su and Zhang 2024).

6 Optimal Chain Pillar Layout and Gas Well Location Under Deep Cover

Casing deformations above the coal seam horizon are largely caused by the relative horizontal displacements along rock strata interfaces. As observed by multi-finger caliper survey and demonstrated by numerical modeling in this study, relative horizontal displacements would induce casing deformations in the form of shear displacement and casing diameter reduction at the interface locations. The amount of relative horizontal displacement mainly depends on overburden depth, massive bed thickness, interface friction, and gas well setback distance from the longwall gob (Su and Zhang 2023; Zhang et al. 2023a); . Under deep cover, the longwall-induced relative horizontal displacements are generally smaller than those under shallow and medium cover (Su 2016, 2017; Scovazzo 2018; Zhang and Su 2021; Zhang et al. 2022b). In addition to geologic factors, gas well location in chain pillars also affects potentially longwall-induced casing deformations. Generally, the further away from the longwall gob, the smaller the relative horizontal displacements and thus smaller the casing deformations. Gas well location in longwall chain pillars is constrained by the size of the chain pillars. To determine optimal pillar layout and gas well location under deep cover, it is important to understand how longwall-induced relative horizontal displacement varies across the chain pillars.

With the established site-specific FLAC3D model (Su et al. 2019b; Zhang et al. 2020), the relative horizontal displacements along two interfaces over the chain pillars are further examined. One interface is at a shallow depth of 58 m and the other interface at a deeper depth of 184 m. Figure 23 shows longwall-induced relative horizontal displacements along the interface at 58-m depth after first and second panel mining. Figure 24 shows longwall-induced relative horizontal displacements along the interface at a 184-m depth after

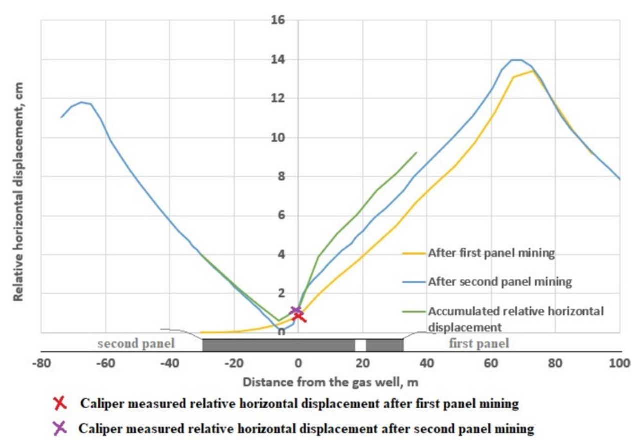

Fig. 23 Longwall-induced relative horizontal displacements along the interface at 58-m depth after first and second panel mining

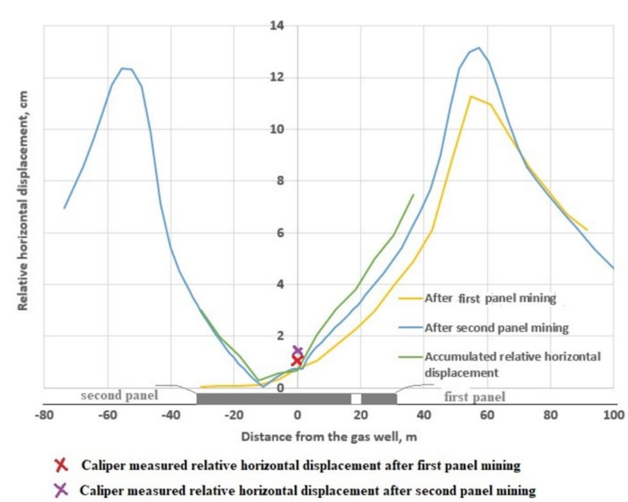

Fig. 24 Longwall-induced relative horizontal displacements along the interface at 184-m depth after first and second panel mining

first and second panel mining. Both figures show that relative horizontal displacements at the interface change with their relative location to the edge of the gob. The peak relative horizontal displacement occurs over the gob and rapidly reduces toward the chain pillars. The incremental relative horizontal displacement induced by second panel mining is smaller than the absolute relative horizontal displacement induced by the first panel mining. The accumulated relative horizontal displacement represents the total relative horizontal displacement. Both figures show that the minimum accumulated relative horizontal displacement occurs within 10 m from the center of the chain pillars. This implies that under deep cover, gas wells near the center of the chain pillar system are subject to smaller lateral ground movements and are likely to have smaller casing deformations above the coal seam horizon. This is also demonstrated by comparing the predicted casing deformations between well #1 and well #8 as shown in Table 5.

Casing deformations at the coal seam are caused by high abutment pressure under deep cover. To minimize potential casing deformations at the coal seam horizon, it is better for gas wells to be placed in a relatively low abutment pressure zone. As shown in Fig. 11, the low abutment pressure zone after second panel mining is almost at the center of the abutment pillar. Based on the abutment pressure distribution as well as the relative horizontal displacement distribution across the chain pillars, the optimal gas well pillar layout is to make the abutment pillar as wide as possible and to place the gas well near the center of the chain pillar system.

7 Limitations

The findings in this manuscript are based on a gas well mine-by case in the Pittsburgh coal seam with site-specific overburden geology and mining conditions. Casing deformations are affected by many factors. Larger casing deformations than predicted and measured in this study could occur due to other atypical factors such as presence of a stream valley, existence of very thick massive strata, larger strata dip, and the existence of a weak claystone floor, which are not included in this study. The overburden depth in this study is considered deep but does not represent all deep cover cases in the Pittsburgh seam. Under deeper cover, casing deformations could potentially occur at the coal seam horizon, and this concern needs to be further addressed. Even though casing deformations did not occur at the coal seam horizon at 314 m overburden depth, it does not mean that casing deformations would not occur at the coal seam horizon under similar overburden depth. The presence of weak claystone in the near-seam horizon and the potential time-dependent deformation of the claystone could cause casing deformations under deep cover.

Since this study represents only the gas well study site at a deep cover of 314 m, more data at similar deep-cover gas well sites are needed to confirm that the conclusions found from this study are applicable to different site conditions. The FLAC3D simulations are purely modeling predictions, within the variance of the variables and parameters used, and need 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.

8 Conclusion

In this site-specific study, a shale gas well located in the chain pillars between two adjacent longwall panels was modeled using the FLAC3D modeling technique for longwall-induced stresses and deformations in the intermediate casing. The predicted casing deformations were compared with the measured deformations from a multi-finger caliper survey. Important conclusions from this research, based on the site-specific geology and conditions from the study site, are made as follows:

- Casing deformations in gas wells in longwall chain pillars above the coal seam horizon occurred at the weak/strong rock interfaces due to relative horizontal displacements along the interfaces. Casing deformations after second panel mining are at the same locations as after first panel mining.
- Under deep cover, casing deformations above the coal seam horizon were small due to high longwall-induced abutment pressure and high frictional resistance along weak/strong rock interfaces. Leaving production casing uncemented from the surface to 30 m below the coal seam can generally eliminate production casing deformations above the mining horizon.
- Casing deformations for gas wells in longwall chain pillars did not occur at the coal seam level under a cover depth up to 314 m because the longwall-induced stress level in the casing is less than its ultimate strength.
- Under deep cover, gas wells near the center of the chain pillar system were subject to smaller lateral ground movements and are likely to have smaller casing deformations above the coal seam horizon.
- Under deep cover, production casing deformations can be minimized by locating gas wells at the center of the chain pillars.

Author Contributions Peter Zhang performed FLAC3D modeling, analyzed field measurement data, and wrote the manuscript. Daniel Su provided technical advice on FLAC3D modeling and the interpretation of the caliper survey data. Mark Van Dyke assisted the interpretation of the gamma log. Bo Hyun Kim provided technical advice on FLAC3D modeling. All authors reviewed and approved the final manuscript.

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Data availability Data are available upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Commonwealth of Pennsylvania, Department of Mines and Mineral Industries, Oil and Gas Division (1957) Joint Coal and Gas Committee, Gas Well Pillar Study. Harrisburg, Pennsylvania, p 28

ITASCA Consulting Group, Inc. (2021) FLAC-3D, Version 7.0, user's guide

Liang S, Elsworth D, Li X, Yang D (2014) Topographic influence on stability of gas wells penetrating longwall mining areas. Int J Coal Geol 172(Mar 2017):31–42

Liang S, Elsworth D, Li X, Fu X, Sun B, Yao Q (2017) Key strata characteristics controlling the integrity of deep wells in longwall mining areas. Int J Coal Geol 132(Oct 2014):23–36

Luo Y, Peng SS, Zhang YQ (1999) Analysis of the observed failure on the inner tubing of the gas well W-510 below the coal seam. Report for Cyprus Cumberland Resources Corp. College of Engineering and Mineral Resources, West Virginia University

Mark C, Agioutantis Z (2018) Analysis of coal pillar stability (ACPS): a new generation of pillar design software: In: Proceedings of the 37th International Conference on Ground Control in Mining. West Virginia University, Morgantown, pp. 1–6

Mark C, Rumbaugh GM (2020) Assessing risks from mining-induced ground movements near gas wells. Int J Min Sci Technol 30(1):11–16

Peng SS (2006) Longwall mining, 2nd edn. West Virginia University

Peng SS, Morsy K, Zhang YQ, Luo Y, Heasley KA (2003) Technique for assessing the effects of longwall mining on gas wells—two case studies. SME Trans 314:107–115

Scovazzo VA, Moran RP (2012) Industry research into gas and oil well protective coal pillar design. In: Proceedings of the 32nd International Conference on Ground Control in Mining. West Virginia University, Morgantown, pp 45–52

Scovazzo VA, Moran RP (2016) Gas well pillar study update. PO 4300311202 and PO 4300400813. Pennsylvania Department of Environmental Protection, Bureau of Oil and Gas Management and John T. Boyd, pp 144

Scovazzo V (2018) Mining effects on gas and oil wells pad NV-35 field experiment field monitoring. In: Proceedings of the 37th International Conference on Ground Control in Mining. West Virginia University, Morgantown, pp 30–43

Su D, Zhang P, Van Dyke M, Minoski T (2019b) Effect of longwall-induced subsurface deformations on shale gas well casing stability under deep cover. Int J Min Sci Technol 29(1):3–8

Su DWH, Zhang P (2023) Longwall-induced deformations and shale gas well casing stresses: engineering principles. In: Proceedings of the 57th US Rock Mechanics Geomechanics Symposium, Atlanta, GA, June 26–28, 2023, p 9

Su DWH, Zhang P (2024) NIOSH gas well stability research: investigation into the cause of an anomalous shale gas well casing deformation at a deep longwall mine. In: 2024 SME Annual Conference & Expo, Phoenix, AZ, February 26–28, 2024

Su D, Zhang P, Dougherty H, Van Dyke M, Minoski T, Schatzel S, Gangrade V, Watkins E, Addis J, Hollerich C (2019a) 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. West Virginia University, Morgantown, pp 49–59

Su DWH (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

Su DWH (2017) Effects of longwall-induced subsurface deformations on the mechanical integrity of shale gas wells drilled over a longwall abutment pillar. In: 2017 SME Annual Meeting, Feb.19–22, 2017, Denver, CO. Preprint 17-051, pp 1–6

Tulu IB, Esterhuizen GS, Mohamed KM, Klemetti TM (2017) Verification of a calibrated longwall model with field measurements. In: Proceedings of the 51st US Rock Mechanics/Geomechanics Symposium, 25–28 June 2017. San Francisco

Wang Y, Watson R, Rostami J, Wang JY, Limbruner M, He Z (2013) Study of borehole stability of Marcellus shale wells in longwall mining areas. J Pet Explor Prod Technol 4:59–71

Zhang P, Dougherty H, Su D, Trackemas J, Tulu B (2020) Influence of longwall mining on the stability of gas wells in chain pillars. Int J Min Sci Technol 30(1):3–9

Zhang P, Su D, Mark C (2021) The current perspective of the PA 1957 Gas Well Pillar Study and its implications for longwall gas well pillars. Int J Min Sci Technol 31(1):117–126

Zhang P, Esterhuizen G, Sears M, Trackemas J, Minoski T, Tulu B (2022c) Roof stability and support strategies associated with longwall-induced horizontal stress changes in belt entries. Min Metal Explor,. https://doi.org/10.1007/s42461-022-00634-9

Zhang P, 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. Houston, Texas

Zhang P, Dougherty H, Su D, 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

Zhang P, Su D, Van Dyke M, Dougherty H (2022a) Shale gas well casing deformation in longwall chain pillars under deep cover—field measurement and numerical modeling. In: Proceedings of the 41st International Conference on Ground Control in Mining, Canonsburg, PA, July 26–28, 2022

Zhang P, Su D, Kim BH, Midler E (2022b) Comparison of measured and modeled casing deformations of a test well in a longwall abutment pillar. In: 56th U.S. Rock Mechanics Geomechanics Symposium, Santa Fe, NM, June 2022, p 9

Zhang P, Su D, Kim B (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, PA, July 25–27, 2023, p 18

Zhang P, Su D, Van Dyke M, Kim BH (2023b) A case study of shale gas well casing deformation in longwall chain pillars under deep cover. In: 57th US Rock Mechanics Geomechanics Symposium, Atlanta, GA, June 26–28, 2023, p 9

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