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Influence of Longwall Mining on the Stability of Shale Gas Wells in Barrier Pillars

Peter Zhang, Daniel Su
NIOSH, Pittsburgh Mining Research Division (PMRD), Pittsburgh, PA, USA
Jun Lu
Consol Energy, Pittsburgh, PA, USA

ABSTRACT: With the shale gas boom over the past decade, many shale gas wells have been drilled through the Pittsburgh coal seam to the Marcellus shale formation. The wells located in longwall barrier pillars are influenced by longwall mining, and their stability has been a safety concern for both the mining and gas industries. This study presented a case in which two longwall panels in the Pittsburgh seam were mined near two shale gas wells in a barrier pillar between the two longwall bleeders. The first longwall panel was mined before the gas wells were drilled and installed in the barrier pillar adjacent to the longwall setup bleeders. The second longwall setup bleeders were developed later on the other side of the barrier pillar, and the second longwall panel was subsequently mined. The stability of the gas wells was evaluated using a numerical modeling approach. The model was set up based on site-specific mining conditions and overburden geology and included sufficient details to simulate the gas well casings, mining sequence, and longwall retreating. The modeling procedures produced realistic results of stresses and deformations around the barrier pillar and in gas well casings, which were verified by in-mine observations.

1. INTRODUCTION

In the eastern United States, there are abundant conventional gas wells drilled through coal seams, which have caused issues for underground coal mining. Conventional shale gas wells are drilled with a traditional drilling method, and gas flows up by natural pressure from the wells. With technology advance in horizontal drilling, gas wells have been drilled first vertically down and then horizontally into deep and tight shale formations to retrieve gas through hydro-fracturing, and these gas wells are known as unconventional gas wells. With the recent shale gas boom, approximately 1,400 unconventional shale gas wells have been drilled through current and future coal reserves in Pennsylvania, West Virginia, and Ohio over the past 15 years (Su et al., 2018b). These shale gas wells have penetrated many coal seams which are either currently mined by or will be mined in the near future. As unconventional wells are drilled deeper, the gas pressure is much higher. For instance, Marcellus shale wells are 1,500–2,700 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 and damaged by longwall mining.

Longwall mining induces surface and subsurface subsidence as well as stress changes in the overburden. When gas wells are influenced by longwall mining, the mechanical integrity of these wells could be compromised by longwall-induced deformations and stresses. If gas well casings are damaged or ruptured, high-pressure gas could migrate into underground workings, potentially causing a fire or explosion. On the other hand, if shale gas well casings are found damaged, the gas wells may need to be plugged or repaired at high cost.

The gas wells penetrating through coal seams have to be protected by coal pillars. The current gas well pillar regulation is based on the PA 1957 gas well pillar study (Commonwealth of Pennsylvania, 1957). The Joint Coal and Gas Committee completed this study on gas well failures caused by coal mining in the state of Pennsylvania. The study included 77 gas well failure cases that occurred over a 25-year span in the room-and-pillar mines with full and partial pillar recovery in the Pittsburgh and Freeport coal seams. The mining depth in those mines ranged from 17 m to 235 m. Longwall mining was not practiced at that time, and the room-and-pillar mining with pillar recovery was the primary underground mining method. The 1957 study provided guidelines for pillar sizes around gas wells under different overburden depth up to 235 m, which became a gas well pillar regulation in Pennsylvania as well as for other states.

As the 1957 study was based on room-and-pillar mining, it is not applicable for modern longwall mining, particularly under deep cover. However, without specific technical guidelines for gas well pillars for longwall mining, the 1957 study is still used to assess the gas well pillars in longwall mines. In 2012, upon realizing 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 performance of gas well casings in longwall chain pillars. Four test wells within a longwall chain pillar were monitored and the results were published by Su (2016, 2017), Scovazzo (2018), and Scovazzo and Moran (2012, 2016). This study provided valuable data for understanding subsurface movements in the vicinity of longwall mining and for evaluating potential gas well failures in both chain pillars and barrier pillars.

Barrier pillars are generally larger and the gas wells in the barrier pillars are farther away from the longwall gob. Therefore, longwall-induced abutment pressure and subsurface deformations at the gas well locations are much smaller. However, the risk of gas well failure still exists, and a thorough evaluation is still necessary to ensure safety for both longwall mining and gas production.

This paper presents a case in which the influence of longwall mining on the stability of shale gas wells in barrier pillars was evaluated. In this case, two longwall panels in the Pittsburgh coal seam were mined near two Marcellus shale wells in a barrier pillar between the two longwall bleeders without safety issues. The paper uses a FLAC3D numerical modeling approach to evaluate the stability of the gas wells in the barrier pillar. In addition to the case study, the paper discusses in general how geological and mining factors can influence the stability of the shale gas wells in barrier pillars.

2. MINING AND GEOLOGICAL CONDITIONS AT THE STUDY SITE

In this case, two unconventional shale gas wells are located within a barrier pillar between two longwall setup bleeders. Figure 1 shows the location of the gas wells and longwall panel layout. The setup bleeders are a set of entries and crosscuts developed for longwall equipment transportation during the longwall face setup as well as for ventilation of the return air after the longwall retreating begins. The first longwall panel (panel I) was mined before the gas wells were drilled and installed. The gas wells were drilled within the center of a 45-m-wide (rib-to-rib) barrier pillar. The setup bleeders for the second panel (panel II) were developed later, and the second panel was mined about 107 m away from the gas wells. The bleeders for the first panel were driven on 27-m × 30-m × 20-m centers, and the bleeders for the second panel were developed on 37-m × 24-m × 21-m centers. The panel width was 336 m for the first panel and 351 m for the second panel. The overburden depth at the gas well site was 259 m. The average mining height of the two longwall panels was approximately 2.1 m.

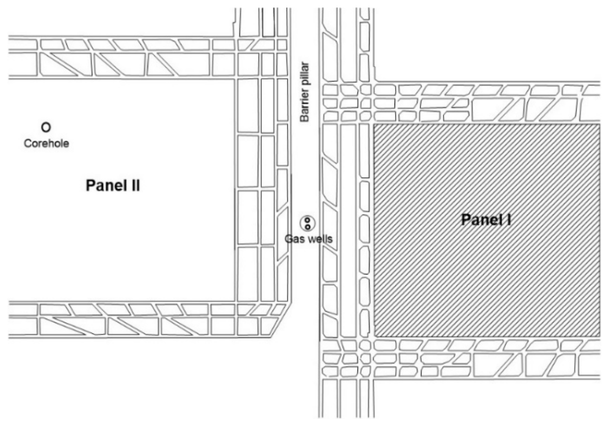

Fig.1. Longwall panel layout near the gas wells.

Figure 2 shows the geologic column of a corehole near the coal seam about 400 m from the gas wells. The overburden strata generally consisted of shale, sandy shale, claystone, sandstone, shaley limestone, and limestone. The coal seam was about 2.1 m thick. The immediate roof consisted of shale, sandyshale, claystone, and sandstone, and the immediate floor was shale, sandy shale, limestone, and claystone. A claystone layer of 0.5 m was present 0.9 m below the coal seam. The corehole constitutes the primary overburden geology input to the FLAC3D model.

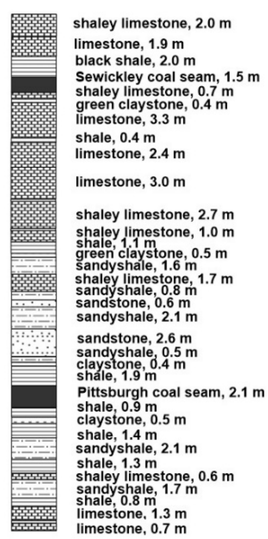

Fig.2. Geologic column of the corehole closest to the gas well.

3. EFFECT OF LONGWALL-INDUCED SUBSURFACE DEFORMATIONS ON THE GAS WELLS IN BARRIER PILLARS

NIOSH researchers develop standardized FLAC3D numerical models to model longwall-induced stresses and strata movements around the longwall panels (Tulu et al., 2017). The modeling procedures produce realistic results of stresses and deformations around the longwall pillars. The pillars, roof, floor, and overburden are modeled to achieve a full-scale, three-dimensional longwall model from the underground mining level to the surface. One advantage of the model is that it allows researchers to investigate not only the stress distributions but also the surface subsidence and strata deformations around the longwall panel.

In this study, a FLAC3D model is set up based on the geological and mining conditions near the gas wells as described above (ITASCA, 2017). The model includes sufficient details to simulate the mining sequence and longwall retreating. The modeled overburden depth is 259 m. Figure 3 shows the sectional view of the FLAC3D model. The full-scale model extends 244 m below the coal seam and 259 m above the coal seam up to the surface. The overburden strata is modeled by ubiquitous joint material, and the rock lithology in the overburden is obtained from the corehole closest to the gas wells. The strength of the ubiquitous joint material is defined by the joint cohesion of 0.5 Mpa, joint tension of 0.2 Mpa, and joint dilation and friction angle of 7^0. Bedding planes between rock types with large differential bending stiffness are modeled with interfaces. Table 1 shows the rock properties used in the model. The Mohr-Coulomb failure criterion is used for the coal pillar, immediate roof, and floor. The gob is modeled by strain-hardening material implemented by the FISH scripting language available in FLAC3D. Horizontal stresses are applied to the model by a horizontal-to-vertical stress ratio with a value of three in the direction parallel to the panel and a value of two in the direction perpendicular to the panel. The entire model consists of about 200,000 elements and 63 interfaces.

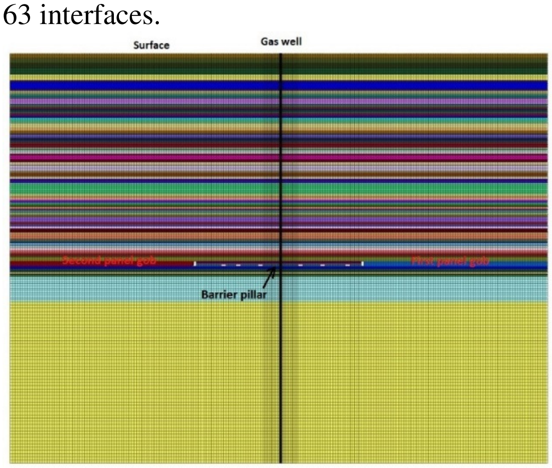

Fig.3. Sectional view of the FLAC3D model.

To model the effect of the two longwall panels on the subsurface movements at the gas wells, the actual sequence of the longwall mining and gas well installation is simulated. The gas wells are installed after the first panel is retreated but before the bleeders for the second panel are developed.

Figure 4 shows the final surface subsidence profiles predicted by the numerical model after both panel I and panel II are mined. The model predicts about 1.4 m of maximum subsidence around the center of the panels, 12 cm of subsidence at the edge of the panels, and less than 5 cm of total subsidence at the gas well site. For model validation, the figure also shows the surface subsidence measured in an adjacent mine under similar mining conditions, and the modeled subsidence agrees very well with the measured subsidence.

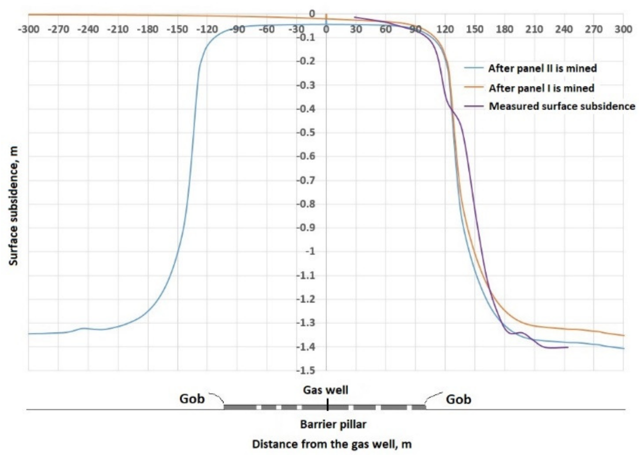

Fig.4. Surface subsidence predicted by the numerical model.

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	2,480	0.35	1.9	28	0.3
claystone	2,900	0.3	1.9	28	0.3
shale	11,600	0.25	11.7	35	4.5
sandyshale	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
shaley limestone	17,400	0.22	14.5	38	5.9
shaley sandstone	15,000	0.22	11.7	38	4.8
siltyshale	11,600	0.25	11.7	32	4.2

Figure 5 shows the vertical stress distribution at the Pittsburgh Seam level across the bleeder pillars after panel I is mined and then after panel II is mined. It is important to note that the longwall-induced vertical stress at the gas well location at the Pittsburgh Seam level is about 0.7 Mpa after panel I is mined, and another 0.7 Mpa after panel II is mined. In other words, longwall mining of panel II is expected to induce about a 0.7-Mpa vertical stress increase at the seam level at the gas well location.

Figure 6 shows the vertical displacement in the subsurface along the gas wells after panel I and panel II are mined. The maximum vertical displacement at the surface is about 2 cm after panel I is mined and 4.4 cm after panel II is mined. Since the gas wells are installed after the panel I is retreated, mining of panel II would induce about 2.4 cm of vertical displacement at the gas well site on the surface. The vertical displacement along the gas wells in the subsurface gradually reduces down to about 2.4 cm at the coal seam level after panel II is mined. Overall, the gas wells are shortened for about 1.2 cm between the surface and the coal seam.

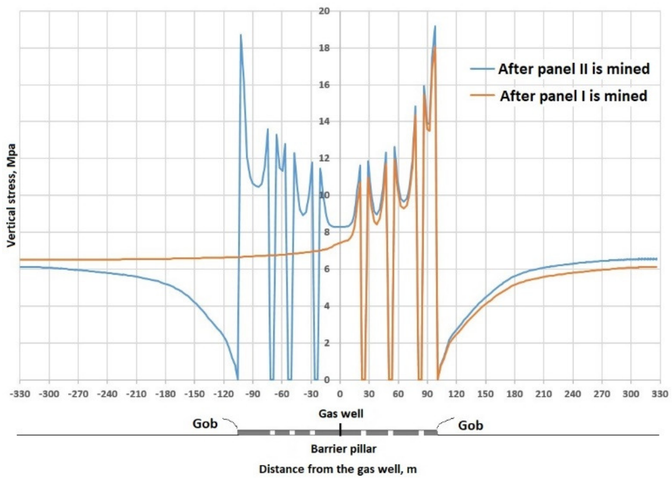

Fig.5. Vertical stress distribution at the coal seam level predicted by the numerical model.

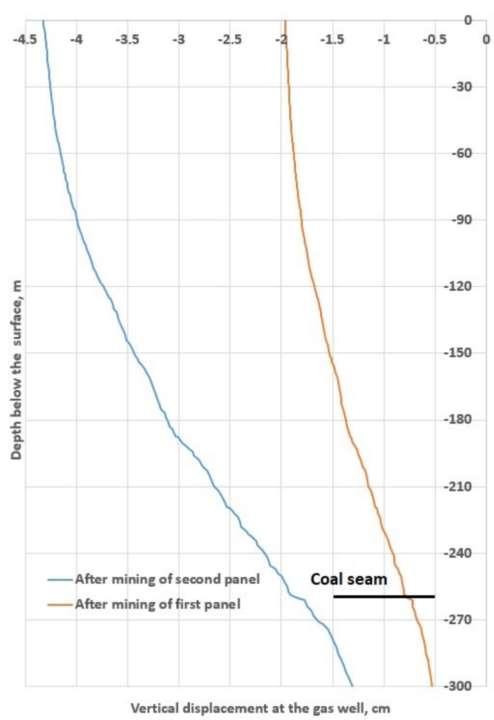

Fig.6. Vertical displacement at the gas well after panel I and panel II are mined.

Figure 7 shows the horizontal displacement in the subsurface along the gas wells after panel I and panel II are extracted. The maximum horizontal displacement at the surface is 3.2 cm after panel I is mined and -0.7 cm after panel II is mined. It is important to note that the direction of the longwall-induced horizontal displacement would be towards the gob. Thus, after the first panel is mined, the ground moves towards the first panel. However, the ground would move back towards the second panel after the second panel is mined. Since the gas wells are installed after the first panel is mined, mining of the second panel would effectively induce about 3.9 cm of horizontal displacement at the gas well site on the surface. The horizontal movement reduces at deeper depth and diminishes to almost zero near the coal seam level.

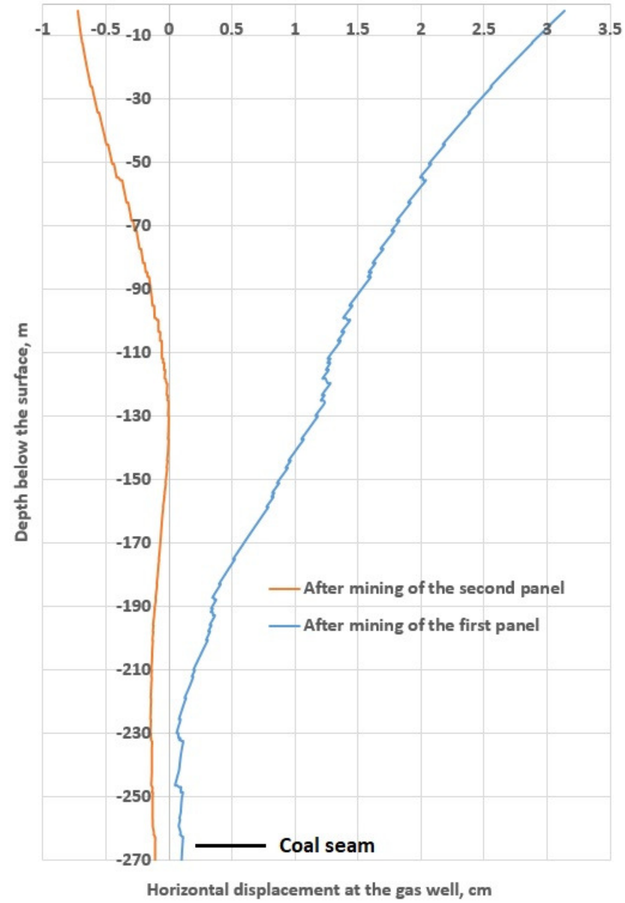

Fig.7. Horizontal displacement at the gas well after panel I and panel II are mined.

4. EFFECT OF SUBSURFACE MOVEMENTS ON THE STABILITY OF GAS WELL CASINGS

Unconventional shale gas wells are generally completed with five casings: surface casing, water protection casing, coal protection casing, intermediate casing, and production casing. The coal protection casing is installed for gas wells that penetrate through coal seams and are usually placed down to 75 m below the coal seams. Figure 8 shows the casings constructed in the FLAC3D model. The annuli between inner casings and between the outer casing and surrounding rock are modeled with cement fillings.

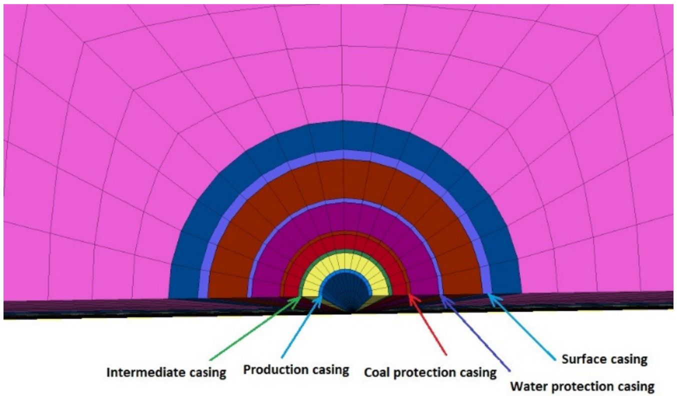

Fig.8. Casings in the numerical model.

Longwall-induced subsurface movements transfer deformations to the gas well casings through back-filled cement. As the modulus of steel is high, a small amount of subsurface movement will induce high stresses in the casings. In response to subsurface movements, the casings are likely to experience vertical compression or tension, horizontal compression, bending, and shear.

The vertical stress in the casings can be induced by differential vertical movement in the subsurface as well as by the weight of the casings. Figure 9 shows the vertical stress in coal protection casing. The high vertical stress in the coal protection casing is found at weak layers such as claystone and coal seam with low elastic modulus and high compressive strain. The highest vertical stress occurs in the casing at the claystone layer in the immediate floor. The tensile stress in the casing is also found in the upper portion of the casing. It should be noted that even though the casing is shortened from the coal seam to the surface as a result of abutment pressure, the upper portion of the casing can still experience tension due to a slight uplifting of the overburden near the surface over the barrier pillar.

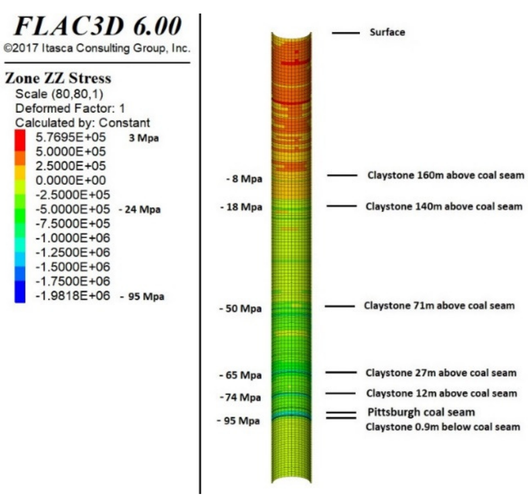

Fig.9. Vertical stress in coal protection casing.

The differential horizontal movement along bedding planes in the subsurface induces shear stress in the casings. Figure 10 shows the shear stress in coal protection casing. High shear stress occurs at the horizons with weak claystone layers. Shear stress induces shear deformation and such deformation is found at the claystone layers along the coal protection casing as shown in Figure 11. It should be pointed out that shear movement along a weak layer would also induce horizontal compressive stress in the casings in addition to shear stress. The amount of the induced horizontal compressive stress could be high if the shear displacement is high.

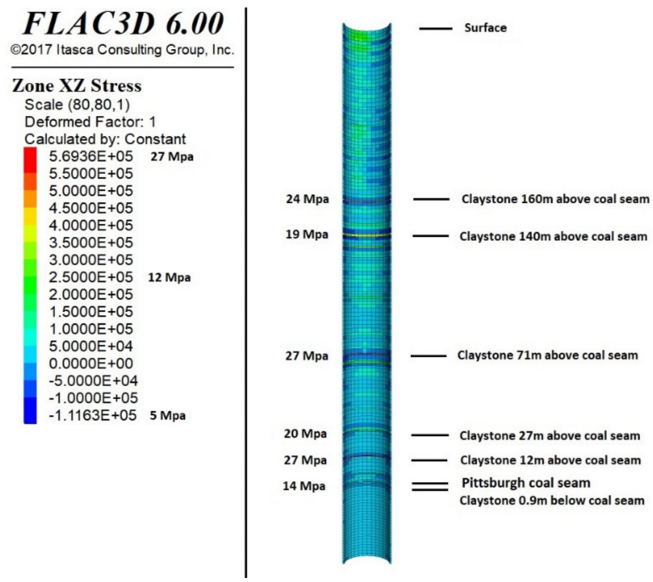

Fig.10. Shear stress in coal protection casing.

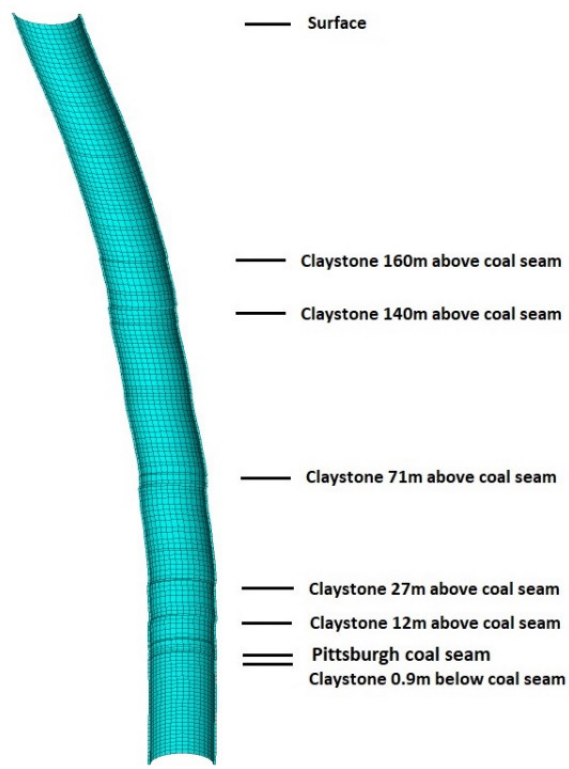

Fig.11. Shear deformation along the coal protection casing.

Under the influence of subsurface movements and induced stresses in the casings, the stability of the steel casings can be evaluated by the von Mises failure criterion. The von Mises equivalent stress in FLAC3D is calculated using the following equation:

$$\sigma_{eq} = \sqrt{3J_2} = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \quad (1)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the three principal stresses.

Figure 12 shows the von Mises equivalent stress in three casings after panel II is mined. High von Mises stress occurs at the weak claystone layers and also increases with depth. Based on the von Mises failure criterion, the casings will yield if the von Mises equivalent stress is greater than the yield strength of the steel. In this case, the peak von Mises stresses are 92 Mpa, 83 Mpa, and 76 Mpa in three casings, which are well below the yield strength for each of the three casings. Therefore, the gas well casings in the barrier pillar in this case are stable under the longwall-induced abutment pressure and subsurface deformations.

When gas wells are located in a barrier pillar with longwall panels on both sides, the sequence of longwall retreating and the timing of gas well installation would affect the induced stresses and deformations in the casings, and thus the stability of the gas wells. If the gas wells are drilled and installed after the longwall panels on both sides are mined, the influence of longwall mining on the gas wells is minimal. The influence is greatest if the gas wells are installed before the first panel is retreated. In this case, the sequence of gas well installation is also simulated by assuming that the gas wells are installed before the first panel is retreated, and the von Mises equivalent stress is calculated as shown in Figure 13. The figure shows that the peak von Mises equivalent stresses in the three casings increase slightly but still less than the yield strength of the casings.

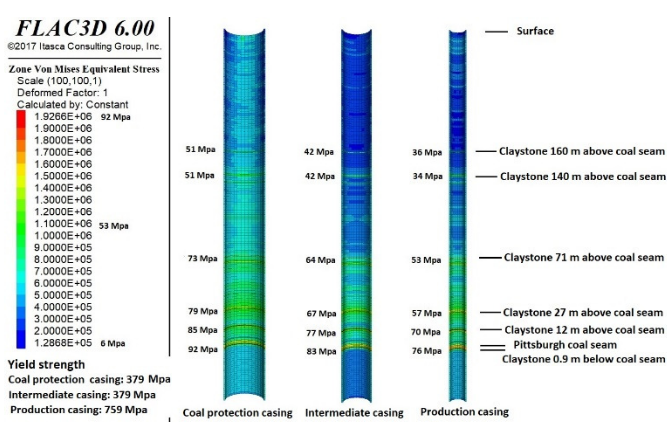

Fig.12. Von Mises stress in three casings after the second panel is mined and with the gas well drilled after the first panel is mined.

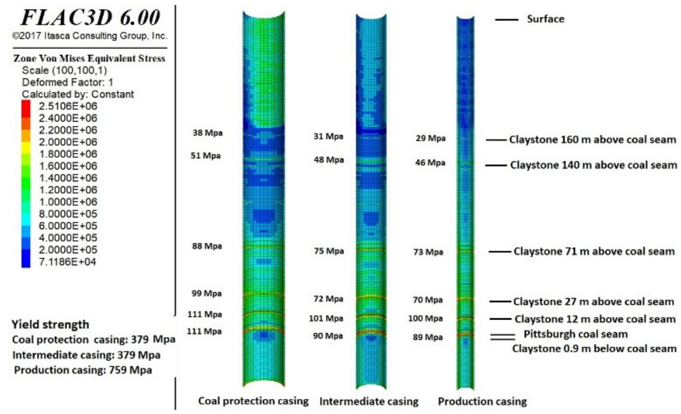

Fig.13. Von Mises stress in three casings after the second panel is mined and with the gas well drilled before the first panel is mined.

5. CRITICAL FACTORS TO INFLUENCE THE STABILITY OF THE GAS WELLS IN BARRIER PILLARS

Gas wells in barrier pillars are influenced by many factors such as overburden depth, abutment pressure, gas well location, overburden geology, and the construction of the gas wells. Pillar stability and surface subsidence may appear critical at first, but they are not enough to infer how subsurface around the gas wells in barrier pillars are disturbed by longwall retreating. As the size of barrier pillars is relatively large and the gas wells are located at some distance away from the edge of the longwall panels, the stability of the barrier pillars is rarely a concern. Even though the surface subsidence at the gas wells is predictable, it does not provide a clear indication on how subsurface movements could occur along the gas wells.

Overburden depth and location of gas wells have a great influence on the stability of the wells in barrier pillars. The overburden depth and location of the gas wells would determine the amount of abutment pressure at the wells. When the gas well is beyond the abutment pressure influence zone, the induced vertical stress at the gas wells is very small. When the gas wells are located within the abutment pressure zone, the distance of the wells from the edge of the gob would have a great effect on the stability of the wells. Figure 14 shows failure cases of gas wells and their distance to the mined gob under different overburden depth. Most of the failure cases are from the PA 1957 gas well pillar study, but two failure cases occurred in the longwall chain pillars in the Pittsburgh coal seam. All of the failures occurred within about 30 m from the gob edge. These failure cases indicate that the risk of failure is high when the gas wells are located within about 30 m from the gob edge. The gas wells in barrier pillars are usually located beyond that range, and the risk of failure can be either moderate or low.

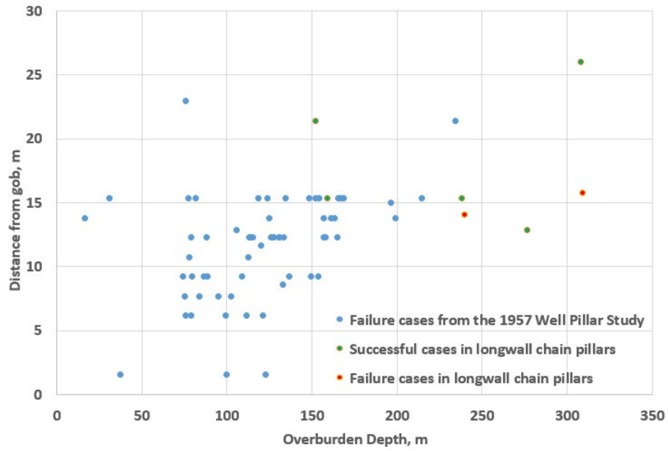

Fig.14. Distance of the failed wells from the mined gob under different overburden depth.

Overburden depth also has influence on where gas well failures could occur in the overburden. Figure 15 shows locations of gas well failure as a result of retreat mining. Based on these available cases, gas well failures can occur in three horizons: in coal seam, within 30 m of roof strata, and within 10 m of immediate floor. The data also shows a trend that with the increase of overburden depth, failures tend to occur either in the coal seam or in the floor. It is important to note that all the failures in the roof strata occurred under shallow overburden depth of less than 150–200 m. The failures in the roof strata are likely to be associated with horizontal shear failure as a result of low friction along the interfaces of bedding planes and lower normal pressure on the bedding planes under shallow overburden depth.

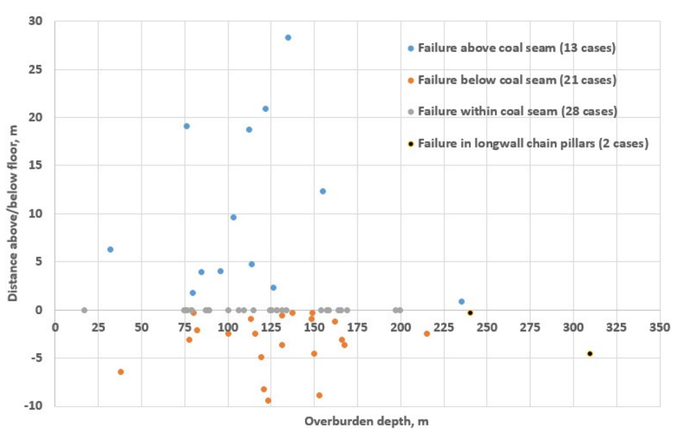

Fig.15. Locations of gas well failure as a results of retreat mining.

Overburden geology, especially weak claystone layers and massive strong sandstone/limestone layers, have a major influence on horizontal displacement in the overburden over a barrier pillar. Weak claystone layers are common in the overburden of the Pittsburgh coal seam, and some claystone layers are typically moisture sensitive. Large deformation can occur at claystone layers due to its low modulus and low friction along the interface with other strong rocks. Figure 16 shows the horizontal displacement along weak/strong interfaces in the overburden above the barrier pillar. The orange-colored curve shows the modeled horizontal displacement at the claystone layer 27 m above the coal seam in this studied case. The other data points are obtained from measurements of horizontal displacement over the gate entry pillars in two longwall mines in the Pittsburgh seam under shallow and deep cover (Su et al., 2018a, and Scovazzo, 2018). All the measured horizontal displacements occurred along the interfaces of weak claystone and strong sandstone/limestone layers. Large horizontal displacements up to 14 cm were measured in the overburden strata under shallow overburden depth of 196 m and are most likely to be associated with low friction along bedding planes and lower normal pressure on the bedding planes. The modeled horizontal displacement curve suggests that the influence zone of the horizontal displacement can extend a large distance over a barrier pillar even though the amount of displacement decreases rapidly away from the gob edge. The horizontal displacement over the barrier pillar is associated not only with subsidence but also with the effect of horizontal stress relief due to creation of the nearby longwall gob. In some cases, the influence zone of horizontal displacement could be greater than the influence zone of abutment pressure. Large horizontal displacement over barrier pillars is more likely to occur at weak/strong interfaces in the overburden under shallow depth, which could potentially induce high shear stress in gas well casings.

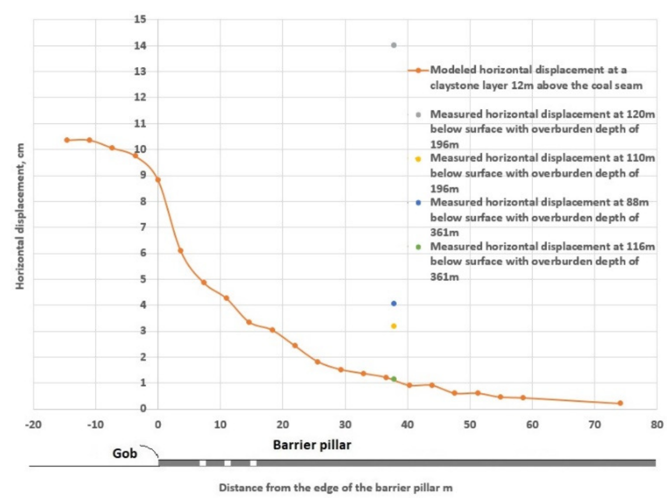

Fig.16. Horizontal displacement in the overburden above a barrier pillar.

The presence of weak claystone layers in the mine floor can also have an influence on gas well stability in barrier pillars, especially when the floor is wet. A claystone floor can induce high vertical and shear stress in gas well casings under deep cover. Therefore, weak claystone layers in the floor, if present, should be incorporated in the numerical model to evaluate their effect on gas well casings.

Under the influence of abutment pressure and subsurface deformations, gas wells are likely to be subject to vertical compression, horizontal compression, and horizontal shear. The potential modes of failure for gas wells penetrated through coal seams are most likely to be buckling failure under vertical or horizontal pressure and shear failure along interfaces between weak and strong layers. For gas wells in barrier pillars, potential failure is more likely to be buckling failure in the coal seam, in the weak claystone floor under deep overburden depth, or shear failure along a weak claystone layer in the overburden above the coal seam under shallow cover.

To assess the stability of the gas wells in barrier pillars, it is important to quantify subsurface movements and their effect on the gas well casings. Numerical modeling is an effective approach to quantify subsurface deformations and induced stresses in the gas well casings by taking into consideration geological and mining factors as well as construction of the gas well casings. The sequence of longwall mining and gas well installation is important and should be incorporated into the numerical model. The stability of the gas wells can be evaluated by the numerically-calculated von Mises stress in the casings.

The influence of longwall mining on the gas wells in barrier pillars is much less than that in longwall chain pillars. Even if the risk of gas well failure in a barrier pillar is perceived low, a thorough assessment should still be performed as any gas leakage from shale gas wells could pose a serious risk. In many cases, the assessment is to determine how much safety precaution should be put into place during longwall retreating. Therefore, it is important to understand and quantify how the gas wells in longwall barrier pillars could be influenced by longwall mining and to make appropriate decisions on what measures should be taken to ensure safety for both longwall mining and gas production.

6. CONCLUSIONS

Based on numerical modeling, field measurement data, and analysis of gas well stability over barrier pillars, the following conclusions can be made:

- A successful case was presented in which two shale gas wells were located in a barrier pillar between two longwall bleeders in the Pittsburgh coal seam and were successfully mined by longwall mining without safety issues.
- Gas wells in barrier pillars are influenced by many factors, such as overburden depth, abutment pressure, gas well location, and overburden geology as well as construction of gas wells.
- Longwall mining induces subsurface movements including vertical, horizontal, and shear at the gas wells in barrier pillars. These movements induce vertical, horizontal, and shear stresses in the gas well casings. Buckling and shear failure in gas well casings are likely to occur under excessive stresses and deformations.
- For gas wells in barrier pillars, potential failure could be buckling failure in the coal seam, in the weak claystone floor under deep overburden depth, or shear failure along a weak claystone layer in the overburden above the coal seam under shallow overburden depth.
- Numerical modeling is an effective approach to quantify subsurface deformations and induced stresses in the gas well casings by taking into consideration the geological and mining factors as well as construction of the gas well casings. Induced von Mises stress in gas well casings can be used to assess the stability of the gas wells in barrier pillars.

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